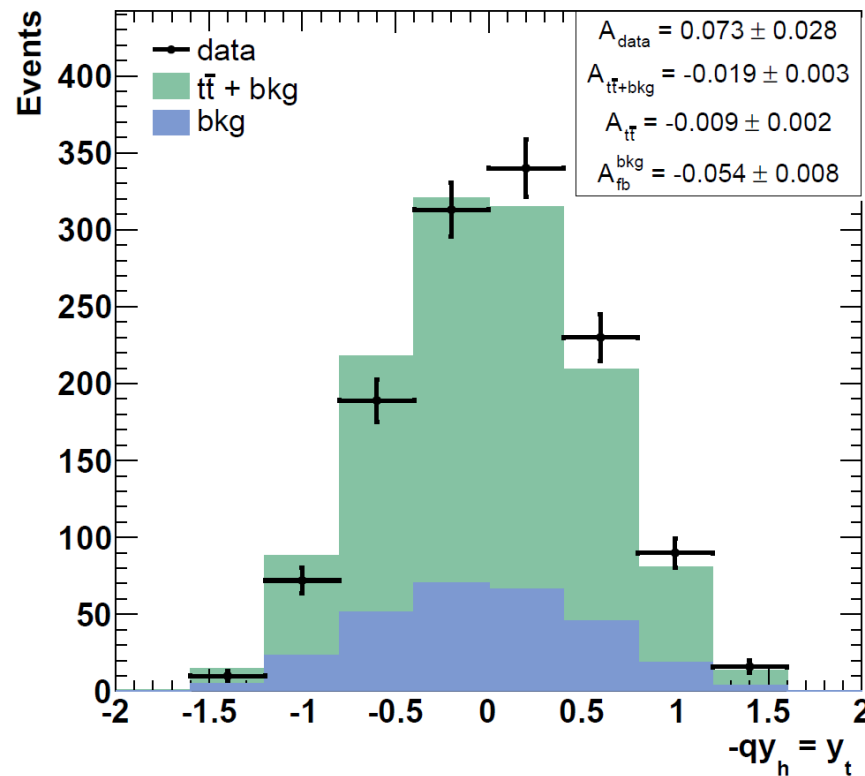# Evidence for a Mass Dependent Forward-Backward Asymmetry in Top Quark Pair Production
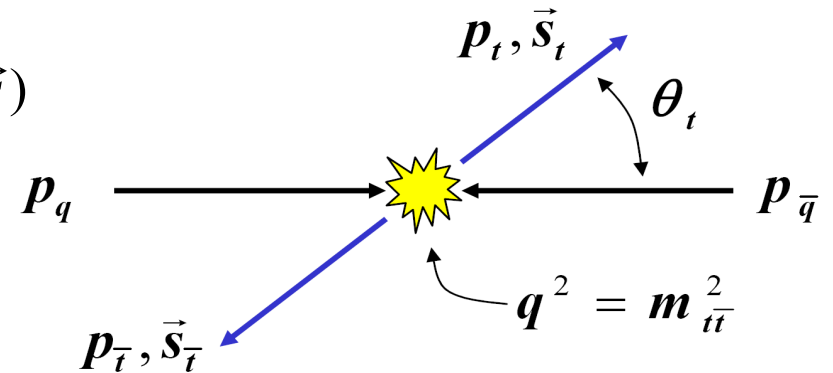
D. Amidei, University of Michigan

for

The CDF Collaboration

Fermilab, Jan. 7, 2010

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top quark pair production

- hard scatter cm-frame cross-section

$$\frac{d\sigma}{d\cos\theta} \propto \frac{\alpha_s^2}{q^2}\left[1 + \cos^2\theta^* + (1-\beta^2)\sin^2\theta^*\right]f(\vec{s})$$

$$p_t, \vec{s}_t$$
$$\theta_t$$
$$p_q \quad\quad p_{\bar{q}}$$
$$q^2 = m_{t\bar{t}}^2$$
$$p_{\bar{t}}, \vec{s}_{\bar{t}}$$

- the final state is specified by

$$\alpha, \ q^2, \ \theta^*, \ \vec{s}$$

- $\alpha, \ q^2$ well measured in total σ and M_{tt} spectrum. SM like.

- here: production angle
    - dependence on $q^2, \ \theta^*$
    - asymmetry in production angle with respect to beamline

top quark pair production

- hard scatter cm-frame cross-section

$$\frac{d\sigma}{d\cos\theta} \propto \frac{\alpha_s^2}{q^2}\left[1 + \cos^2\theta^* + (1-\beta^2)\sin^2\theta^* + \frac{q^2}{q^2 - M^2}\cos\theta^*\right]$$

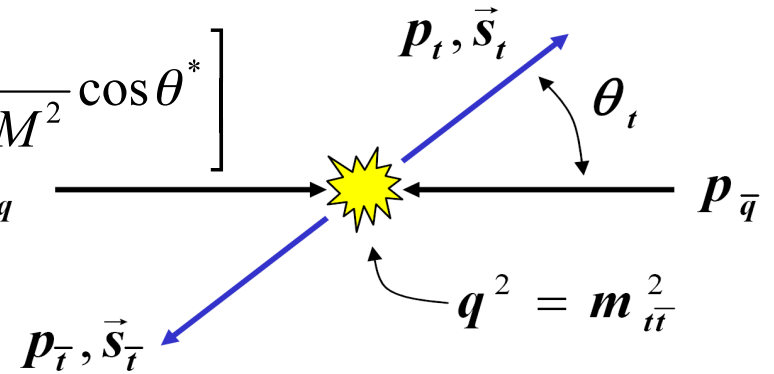$p_t, \vec{s}_t$

θ_t

p_q $p_{\bar{q}}$

$q^2 = m_{t\bar{t}}^2$

$p_{\bar{t}}, \vec{s}_{\bar{t}}$

- the final state is specified by

$$\alpha, \ q^2, \ \theta^*, \ \vec{s}$$

- $\alpha, \ q^2$ well measured in total σ and M_{tt} spectrum. SM like.
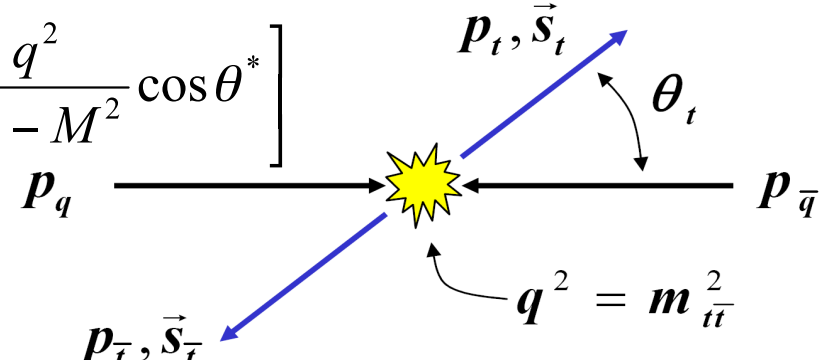
- here: production angle
  - dependence on $q^2, \ \theta^*$
  - asymmetry in production angle with respect to beamline

top quark pair production

- hard scatter cm-frame cross-section

$$\frac{d\sigma}{d\cos\theta} \propto \frac{\alpha_s^2}{q^2}\left[1+\cos^2\theta^* + (1-\beta^2)\sin^2\theta^* + \frac{q^2}{q^2-M^2}\cos\theta^*\right]$$

- the final state is specified by

  $$\alpha,\ q^2,\ \theta^*,\ \vec{s}$$

- $\alpha,\ q^2$ well measured in total σ and M_{tt} spectrum. SM like.

- here: production angle
  - dependence on $q^2,\ \theta^* \longleftrightarrow M_{t\bar{t}},\ \Delta y$
  - asymmetry in production angle with respect to beamline

- Measurement of inclusive, Δy, and M_{tt} dependent asymmetry

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prior measurements

- CDF, 1.9 fb^{-1} , inclusive, corrected to "parton-level"

  - tt rest frame $A^{t\bar{t}} = 0.24 \pm 0.14$

  - NLO QCD $A^{t\bar{t}} = 0.06 \pm 0.01$

                                                      PRL 101, 202001 (2008)

  - lab (pp) frame $A^{p\bar{p}} = 0.17 \pm 0.08$

  - NLO QCD $A^{p\bar{p}} = 0.04 \pm 0.01$

- D0, inclusive, background subtracted "data-level"

  - tt rest frame $A^{t\bar{t}} = 0.12 \pm 0.08$ 0.9 fb^{-1} PRL 100, 142002 (2008)

                           $A^{t\bar{t}} = 0.08 \pm 0.04$ 4.3 fb^{-1} ICHEP 2010

theoretical interest

- exotic gluons
  - massive chiral color
  - RS gluon
  - color sextets, anti-triplets
- IVB´
  - Z´
  - FV W´Z´ t-channel
- FV scalars
- effective Lagrangians

- nice theoretical review by Cao et al. PRD 81,014016, arXiv:1003.3461

- model building must contend with
  - total σ in good agreement with SM
 - $d\sigma/dM_{tt}$ in good agreement with SM

this analysis

- 5.3 fb^{-1}

- standard "lepton+jets" selection, reconstruction

- establish rapidity variables, A_{fb} definitions, in tt frame and lab frame

- models
    - LO
    - QCD charge asymmetry
    - color-octet

- rapidity distributions in the data

- correct the rapidity distributions for
    - backgrounds
    - selection efficiency
    - reconstruction smearing

    to find the model independent A_{fb} to compare to theory

- inclusive in tt and lab frame

- rapidity dependence in tt frame

- M_{tt} dependence in lab frame

top pair production and decay

lepton + jets mode

$$q\bar{q} \rightarrow g \rightarrow t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (l^+\upsilon b)(q\bar{q}\bar{b}) \rightarrow l^+ + \not{E}_T + 4\,j + \geq 1\ btag$$
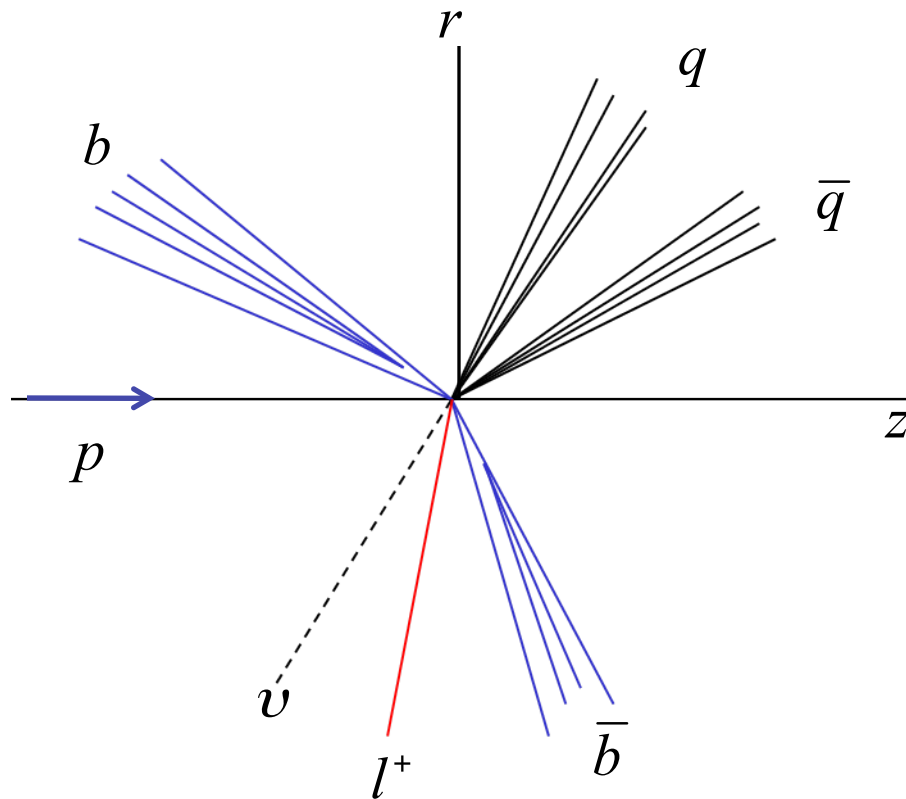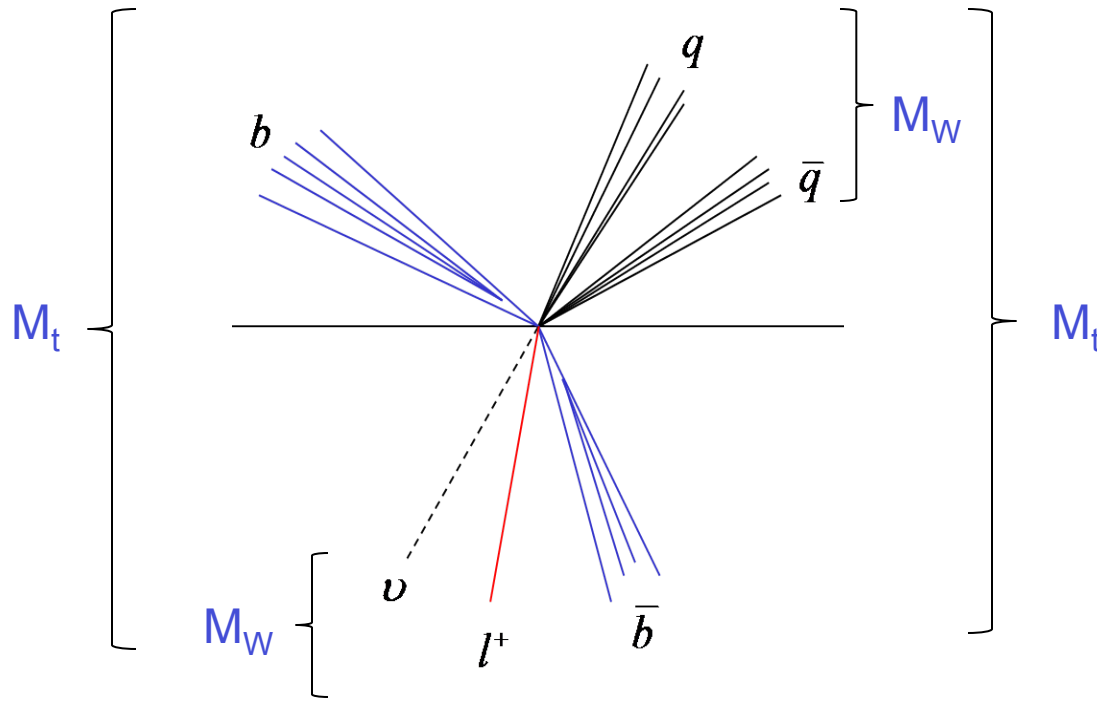

r-z view

event selection

- high p_t lepton (e/μ)
  - $E_t/p_t > 20$ GeV (/c)
  - $|\eta| < 1.0$
- missing $E_t > 20$ GeV
- four jets
  - $E_t > 20$ GeV
  - $|\eta| < 2.0$
- at least one b-tagged jet
  - $|\eta| < 1.0$

- 1260 events
- 283±50 non-tt background
  - established in precision σ measurement
  - mostly W+jets

top reconstruction

$$l^+ + E_T + 4j + \geq 1\ btag \rightarrow (l^+ \upsilon b)(q\bar{q}\bar{b}) \rightarrow (W^+ b)(W^- \bar{b}) \rightarrow t\bar{t}$$

- Jet-parton assignment, $p_z(\nu)$ via minimum of simple χ^2
  - Constraints: M_W = 80.4 GeV/c2, Mt = 175 GeV/c^2, btag = b
  - Float jet p_t within errors

$$\chi^2 = \sum_{lep,\,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{top})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{top})^2}{\Gamma_t^2}$$
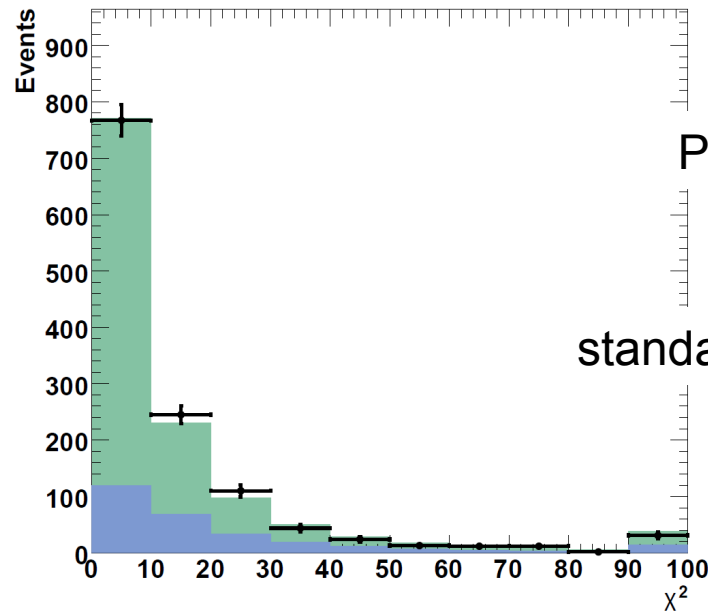

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top reconstruction

$$l^+ + \not{E}_T + 4j + \geq 1\, btag \rightarrow (l^+\upsilon b)(q\bar{q}\bar{b}) \rightarrow (W^+b)(W^-\bar{b}) \rightarrow t\bar{t}$$
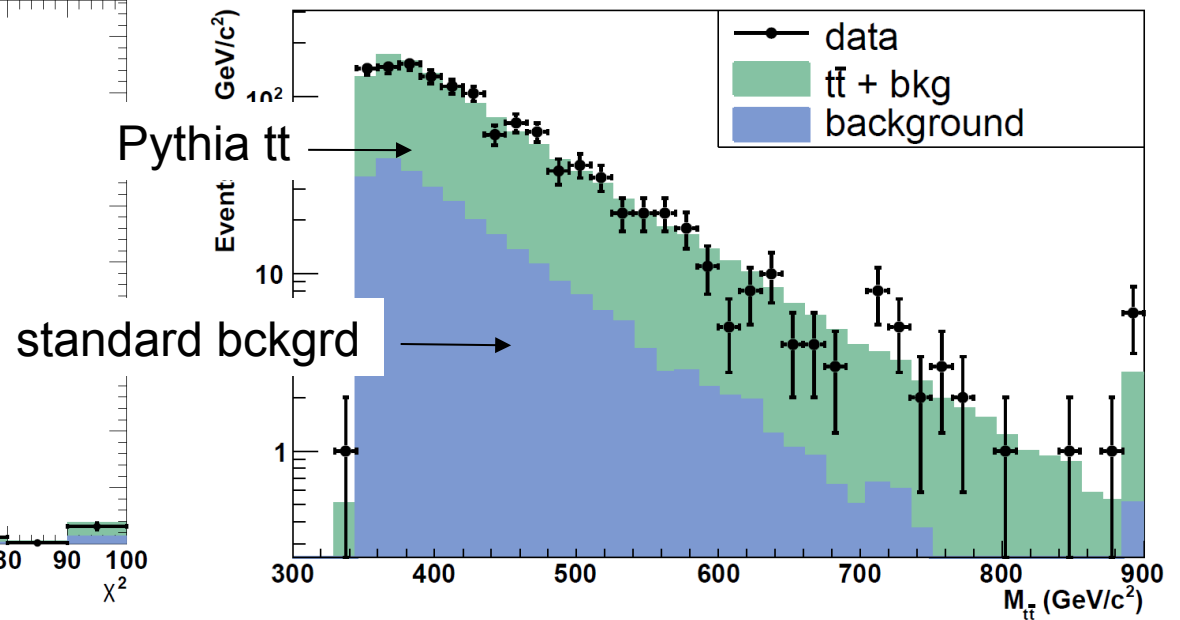
- Jet-parton assignment, $p_z(\nu)$ via minimum of simple χ^2
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  - Float jet p_t within errors

$$\chi^2 = \sum_{lep,\,jets} \frac{(p_t^{i,\,meas} - p_t^{i,\,fit})^2}{\sigma_i^2} + \sum_{j=x,\,y} \frac{(p_j^{UE,\,meas} - p_j^{UE,\,fit})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{top})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{top})^2}{\Gamma_t^2}$$

$$\chi^2 \qquad\qquad\qquad M_{t\bar{t}}$$

rapidity : lab frame

- each event has a t_{lep} and t_{had} decay

$$+ q_l \Rightarrow t_{leptonic} + \bar{t}_{hadronic}$$

$$- q_l \Rightarrow t_{hadronic} + \bar{t}_{leptonic}$$

- and a rapidity for each
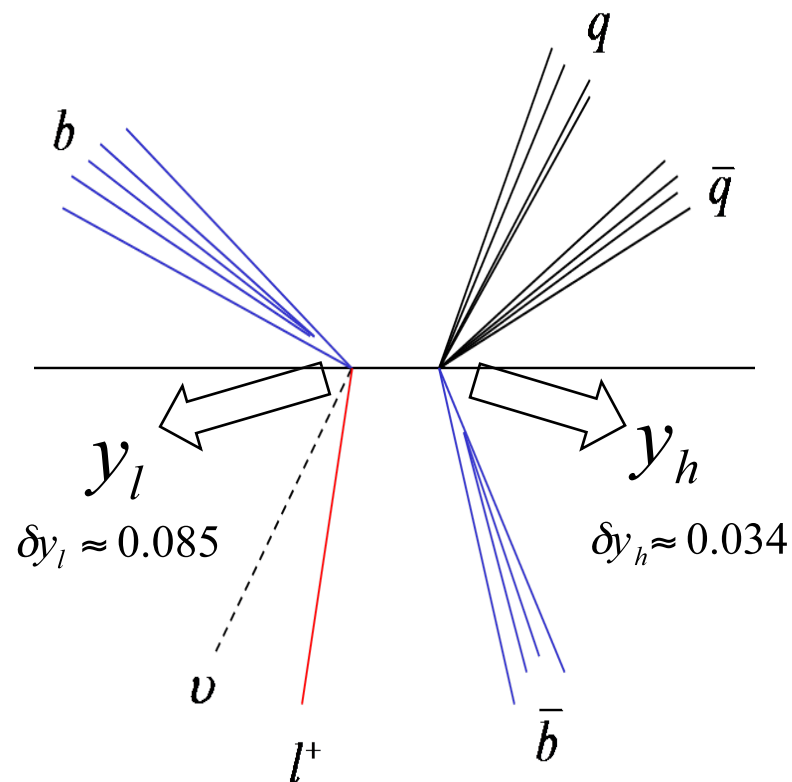
$$y_{leptonic} = y_l$$

$$y_{hadronic} = y_h$$

- simple rapidity variable in lab frame: y_h
  - better measured than y_l
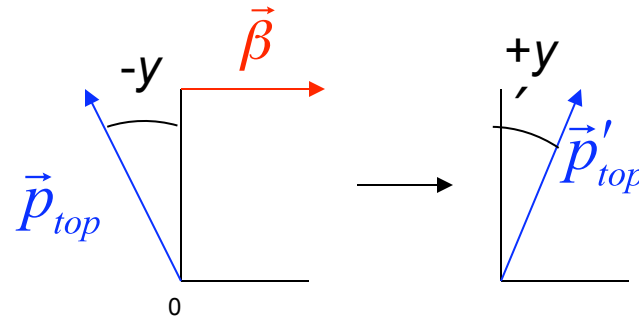 - acceptance out to $|\eta| < 2.0$

- charge tag:
  - assign charge with lepton from t_{lep}
  - interchange of lepton charge $\longleftrightarrow$ interchange of t and $\bar{t}$
  - If assume CP can combine

$$- q \cdot y_h = y_t^{p\bar{p}}$$

q

b

$\bar{q}$

y_l

y_h

$\delta y_l \approx 0.085$

$\delta y_h \approx 0.034$

υ

l^+

$\bar{b}$

rapidity : tt frame

- a longitudinal boost can change the direction of the top quark
  - A is frame dependent!
  - A^{pp} is diluted by the boost

- a frame invariant variable
  - rapidity difference

$$\Delta y_{t\bar{t}} = q \cdot (y_l - y_h)$$
$$= y_t - y_{\bar{t}}$$

  - good : decreased dilution from boost (for NLO QCD effect)

$$A_{FB}^{t\bar{t}} \approx 1.5 \times A_{FB}^{p\bar{p}}$$

  - bad: decreased precision

$$\delta\Delta y \approx 0.100$$

  - great: ease of interpretation:

$$\Delta y_{t\bar{t}} = 2y_t^{t\bar{t}}$$

→ asymmetry in Δy_{tt} is equal to asymmetry in top quark production angle in tt rest frame

asymmetries

- lab frame asymmetry in -qy$_h$

$$A_{FB}^{p\bar{p}} = \frac{N(-qy_h > 0) - N(-qy_h < 0)}{N(-qy_h > 0) + N(-qy_h < 0)}$$

$$= \frac{N(y_t^{p\bar{p}} > 0) - N(y_t^{p\bar{p}} < 0)}{N(y_t^{p\bar{p}} > 0) + N(y_t^{p\bar{p}} < 0)}$$

- tt rest frame asymmetry in Δy:
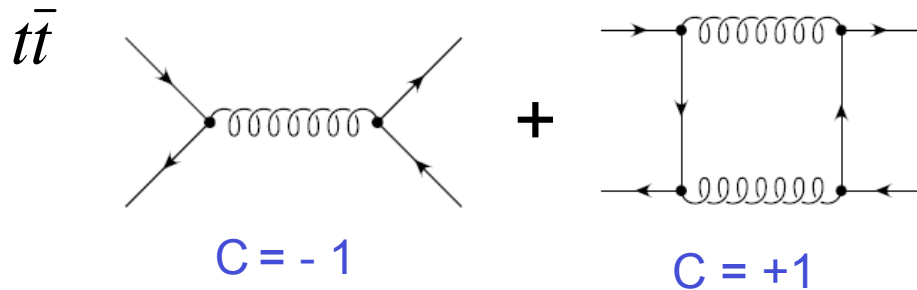
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$$= \frac{N(y_t^{t\bar{t}} > 0) - N(y_t^{t\bar{t}} < 0)}{N(y_t^{t\bar{t}} > 0) + N(y_t^{t\bar{t}} < 0)}$$
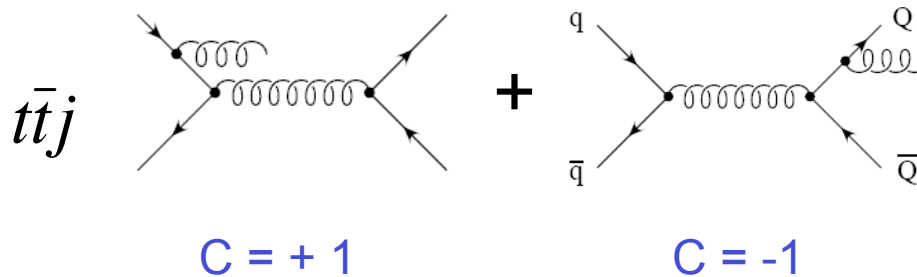
- also of interest: uncharged asymmetries in y_h and y_l-y_h

tt charge asymmetry in QCD

- Halzen, Hoyer, Kim; Brown, Sadhev, Mikaelian; Kuhn, Rodrigo; Ellis, Dawson, Nason; Almeida, Sterman, Vogelsang; Bowen, Ellis, Rainwater

$t\bar{t}$

C = - 1   + 　　　　　　　C = +1

tt frame asymmetries

$A_{FB} \sim$ +10-12 % NLO

$t\bar{t}j$

C = + 1   + 　　　　　　　C = -1

$A_{FB} \sim$ -7 % NLO

_____

$A_{FB} \sim$ 6 +- 1.0 %   net

- tests of C in strong interaction confounded by difficulty of jet charge
- reconstructed top pair system has full information on charge flow
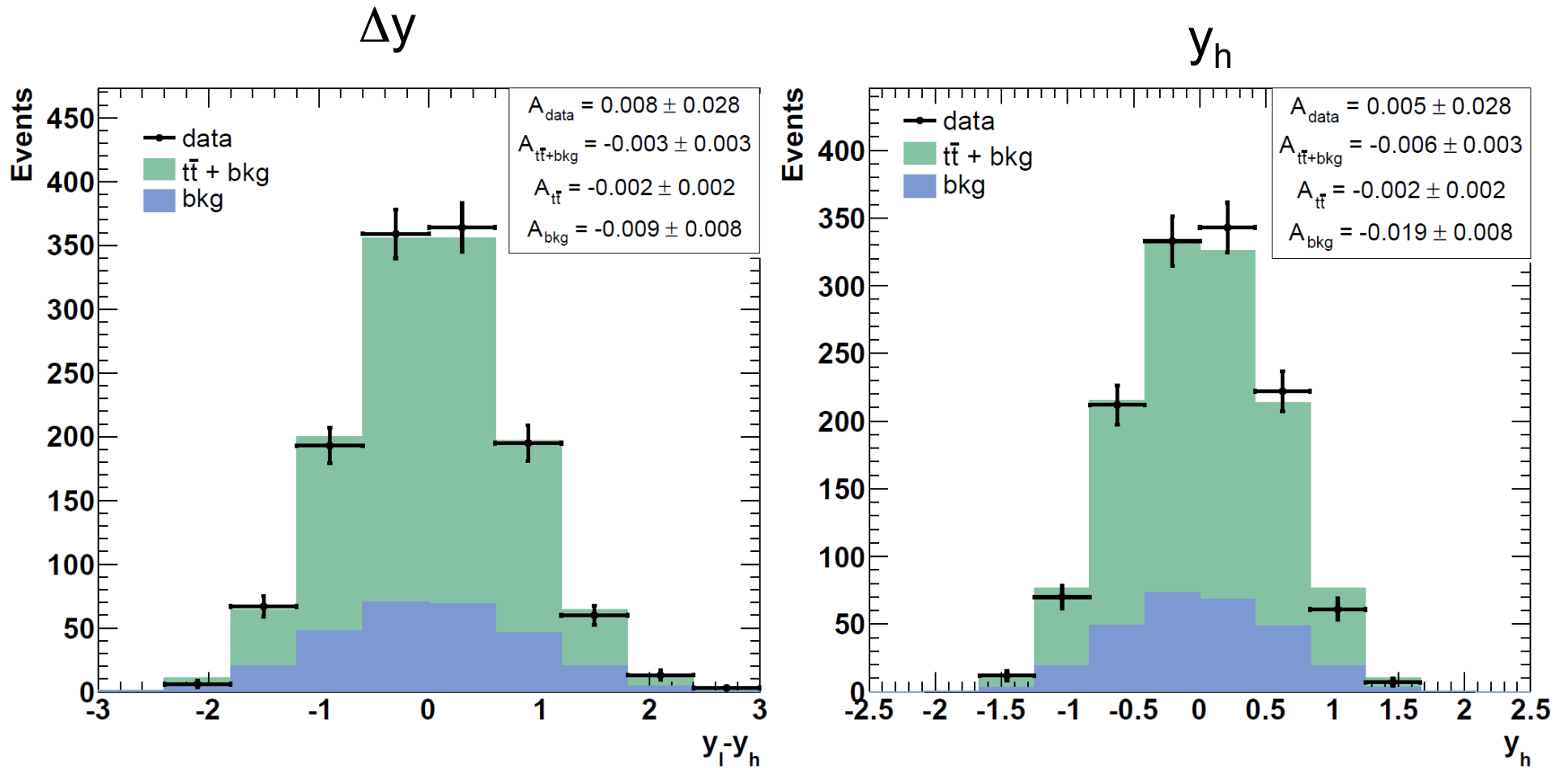 - test C in strong interactions at large q^2

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expected QCD asymmetries

- MCFM NLO calculation at "parton level"
- MC@NLO + CDFSIM

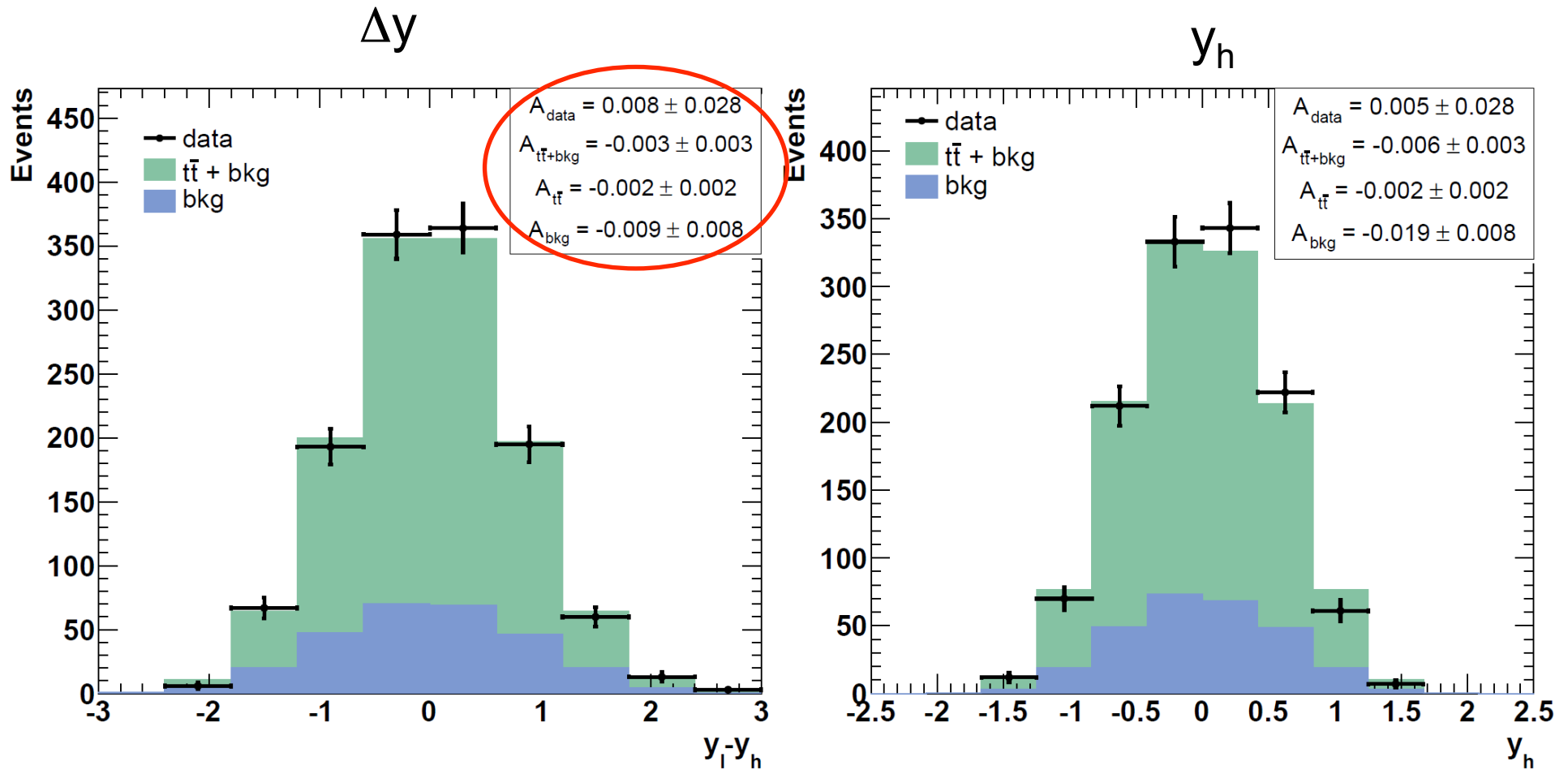| model	level	$A^{p\bar{p}}$	$A^{t\bar{t}}$	
MCFM	parton	0.038 ± 0.006	0.058 ± 0.009	
MC@NLO	parton	0.032 ± 0.005	0.052 ± 0.008	truth
MC@NLO	$t\bar{t}$	0.018 ± 0.005	0.024 ± 0.005	sim + reco
MC@NLO	$t\bar{t}$+bkg	0.001 ± 0.003	0.017 ± 0.004	sim + reco +bkg

- MC@NLO:
  - prediction for data level asymmetry in rest frame is zero!
  - prediction for data level asymmetrry in tt frame < stat precision (0.028)

- Pythia remains good approximation of SM

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inclusive distributions (both lepton charges)

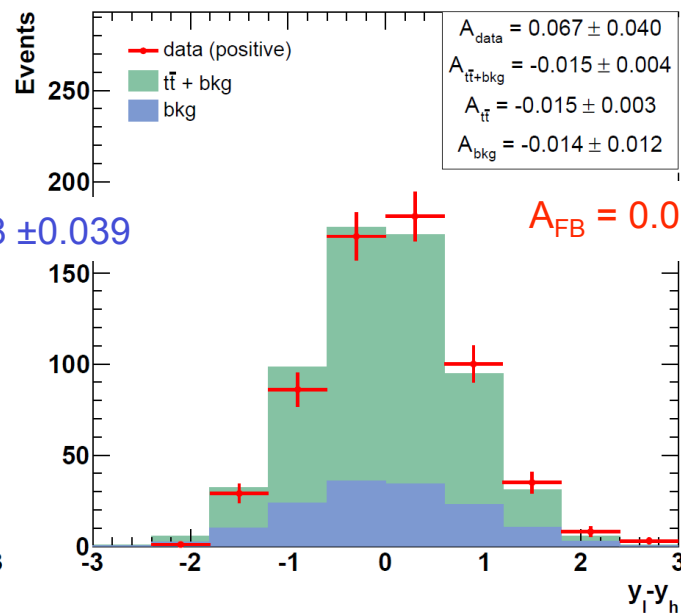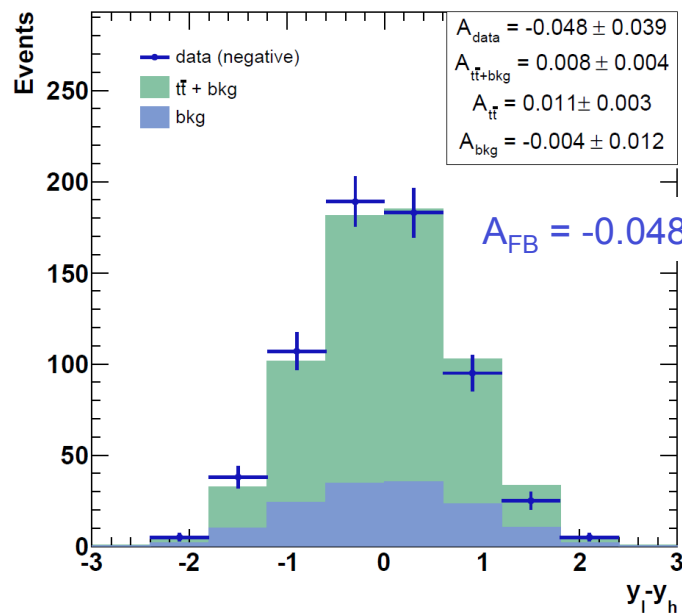- **symmetric!**

inclusive distributions (both lepton charges)

Δy

$A_{data} = 0.008 \pm 0.028$
$A_{t\bar{t}+bkg} = -0.003 \pm 0.003$
$A_{t\bar{t}} = -0.002 \pm 0.002$
$A_{bkg} = -0.009 \pm 0.008$

y_h

$A_{data} = 0.005 \pm 0.028$
$A_{t\bar{t}+bkg} = -0.006 \pm 0.003$
$A_{t\bar{t}} = -0.002 \pm 0.002$
$A_{bkg} = -0.019 \pm 0.008$

- **symmetric!**

separate by lepton charge

negative leptons

positive leptons

Δy

y_h

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separate by lepton charge

negative leptons

positive leptons

Δy

$A_{data} = -0.048 \pm 0.039$
$A_{t\bar{t}+bkg} = 0.008 \pm 0.004$
$A_{t\bar{t}} = 0.011 \pm 0.003$
$A_{bkg} = -0.004 \pm 0.012$

$A_{FB} = -0.048 \pm 0.039$

$A_{data} = 0.067 \pm 0.040$
$A_{t\bar{t}+bkg} = -0.015 \pm 0.004$
$A_{t\bar{t}} = -0.015 \pm 0.003$
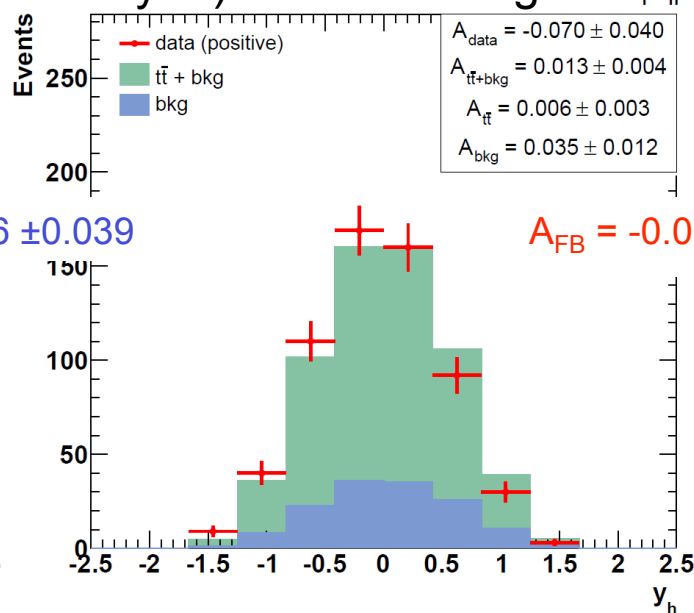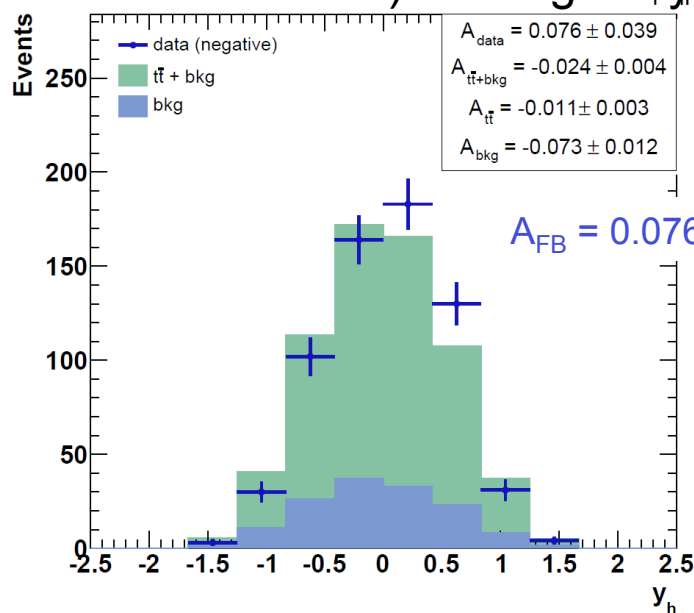$A_{bkg} = -0.014 \pm 0.012$
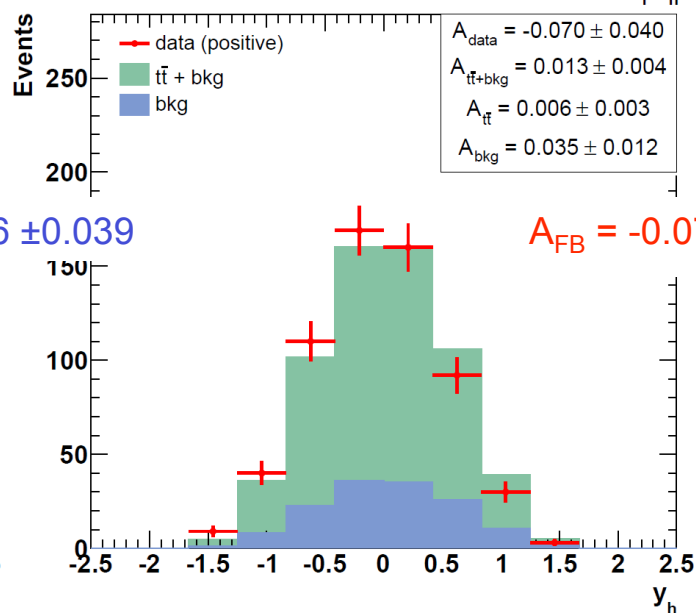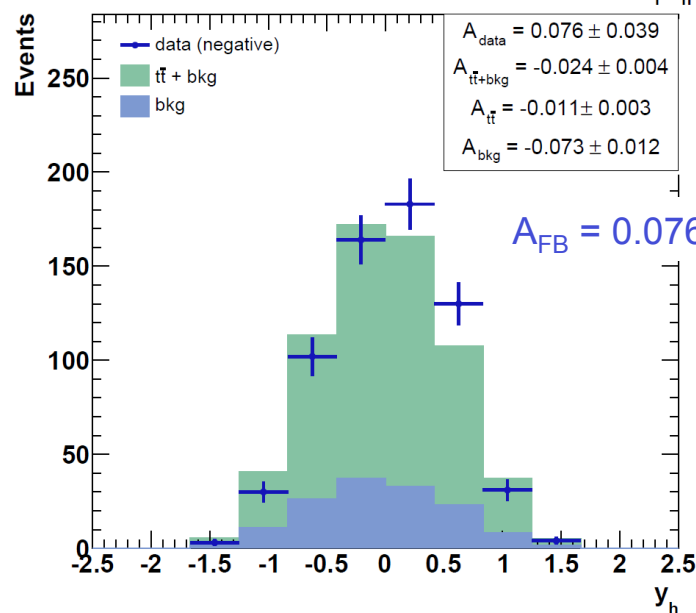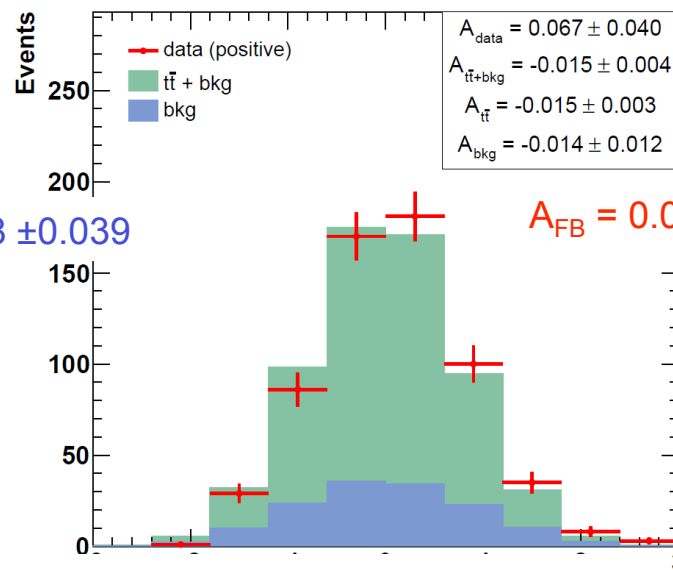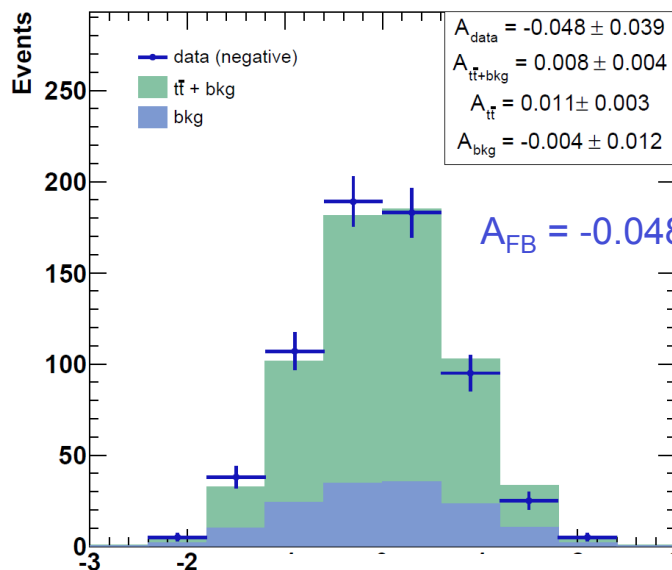
$A_{FB} = 0.067 \pm 0.040$

It's 1) a charge asymmetry 2)CP conserving

y_h

$A_{data} = 0.076 \pm 0.039$
$A_{t\bar{t}+bkg} = -0.024 \pm 0.004$
$A_{t\bar{t}} = -0.011 \pm 0.003$
$A_{bkg} = -0.073 \pm 0.012$

$A_{FB} = 0.076 \pm 0.039$

$A_{data} = -0.070 \pm 0.040$
$A_{t\bar{t}+bkg} = 0.013 \pm 0.004$
$A_{t\bar{t}} = 0.006 \pm 0.003$
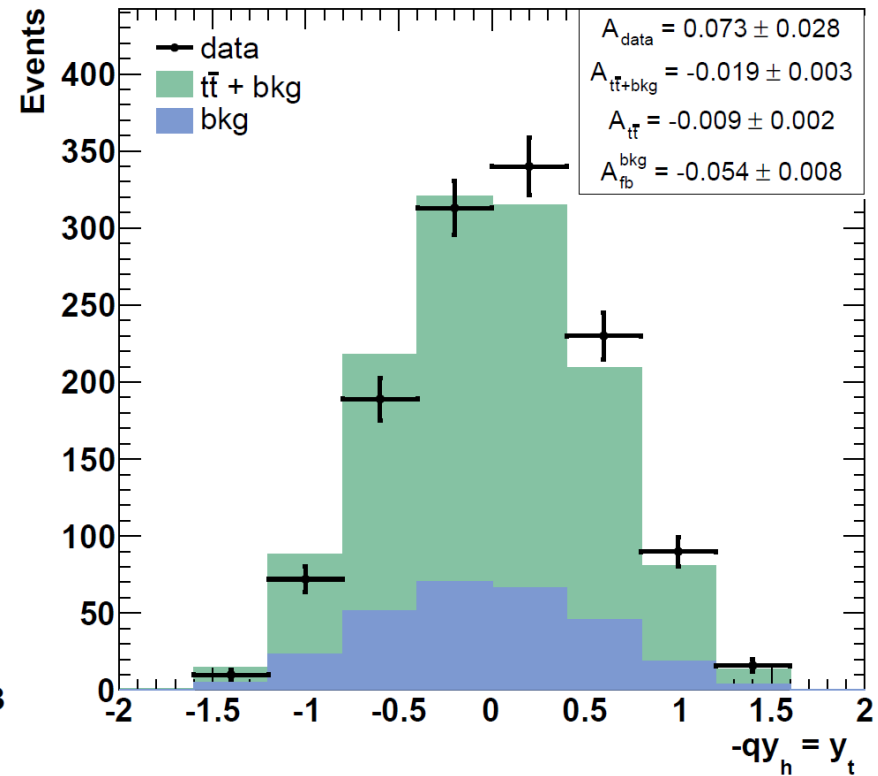$A_{bkg} = 0.035 \pm 0.012$

$A_{FB} = -0.070 \pm 0.040$

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combine charges

tt frame

$A_{data} = 0.057 \pm 0.028$
$A_{t\bar{t}+bkg} = -0.011 \pm 0.003$
$A_{t\bar{t}} = -0.013 \pm 0.002$
$A_{bkg} = -0.005 \pm 0.008$

- data
- $t\bar{t}$ + bkg
- bkg

$\Delta y = y_t - y_{\bar{t}}$

lab frame

$A_{data} = 0.073 \pm 0.028$
$A_{t\bar{t}+bkg} = -0.019 \pm 0.003$
$A_{t\bar{t}} = -0.009 \pm 0.002$
$A_{fb}^{bkg} = -0.054 \pm 0.008$

- data
- $t\bar{t}$ + bkg
- bkg

$-qy_h = y_t$
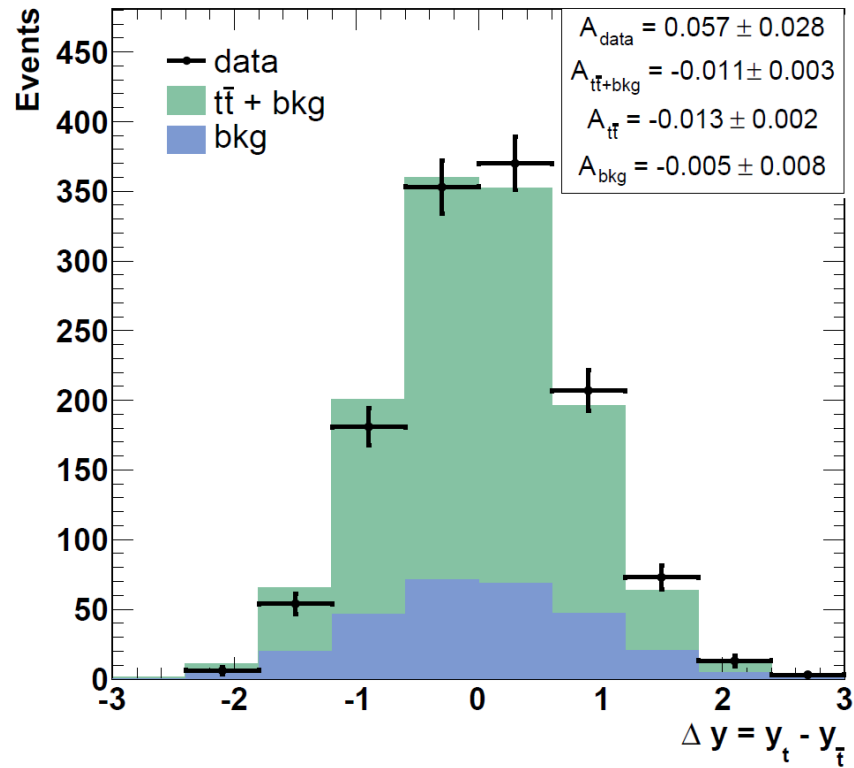
- Combined Δy:
  $A_{FB} = 0.057 \pm 0.028$
- Compare to mc@nlo
  $A_{FB} = 0.024$

- Combined $-q*y_h$:
  $A_{FB} = 0.073 \pm 0.028$
- Compare to mc@nlo
  $A_{FB} = 0.001$

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correct to the parton level

- dN/dy parton level histogram
  - parton level bins j w/ contents P_j
- the top data signal
  - $T_i = S_{ij} \times A_j \times P_j$
- where
  - the A_j are the acceptances for each bin
  - the S_{ij} are the bin-to-bin migration ratios
  - both are estimated with Pythia
- dN/dy data level histogram
  - data level bins i w/ contents D_i
  - Sum of top and bkgrd: $D_i = T_i + B_i$
- to propagate data to parton level:
  - $P_j = A_j^{-1} \times S_{ji}^{-1} \times (D_i - B_i)$
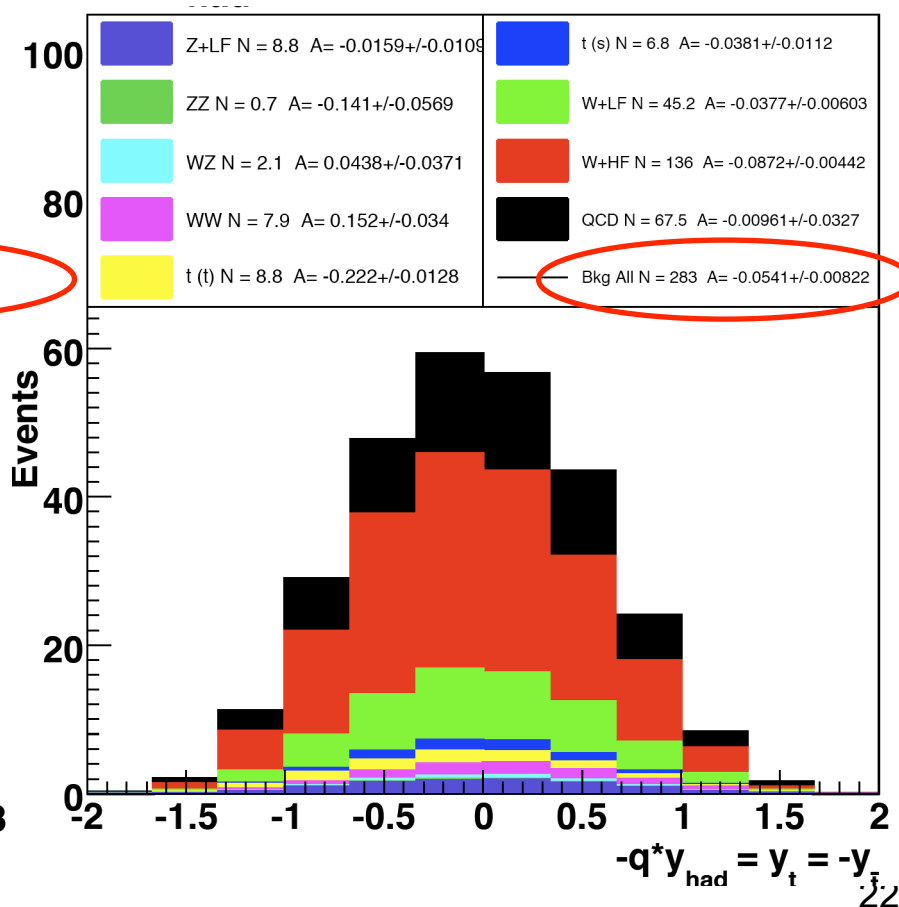- result is optimized when number of bins = 4

backgrounds

- detailed model for all background components

- fully simulated model samples are reconstructed like data
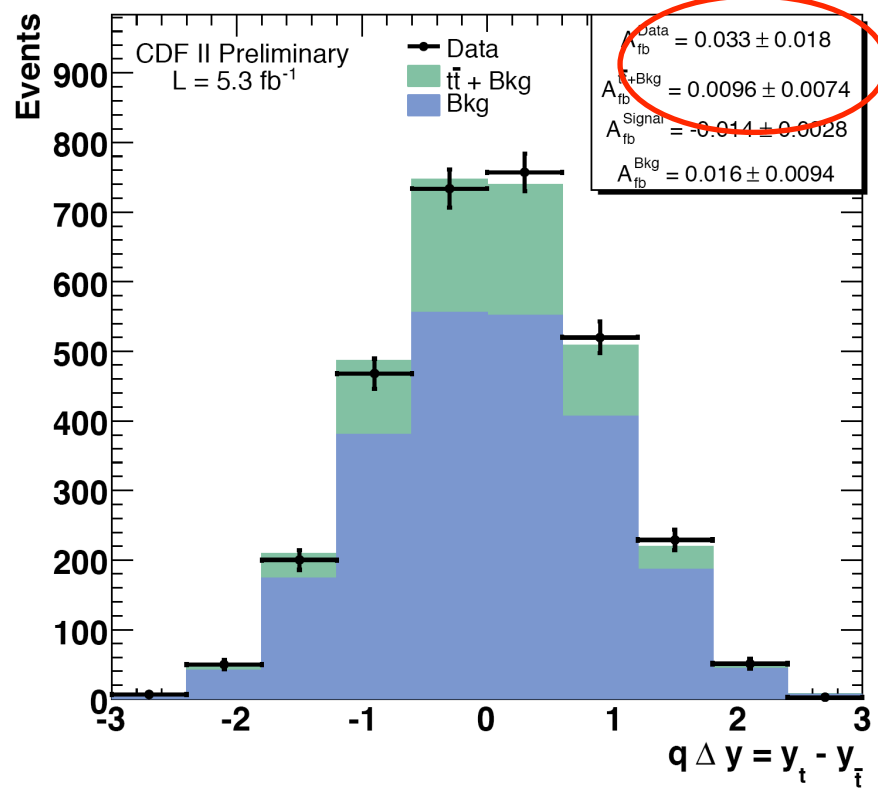
- asymmetries small (but not zero)
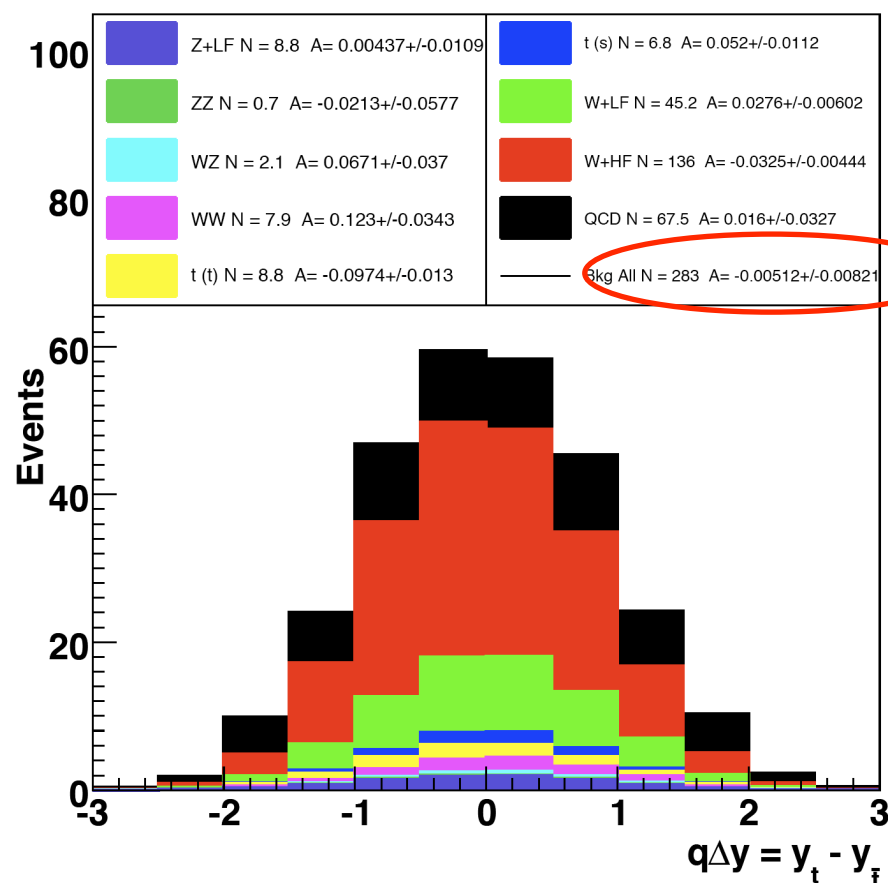
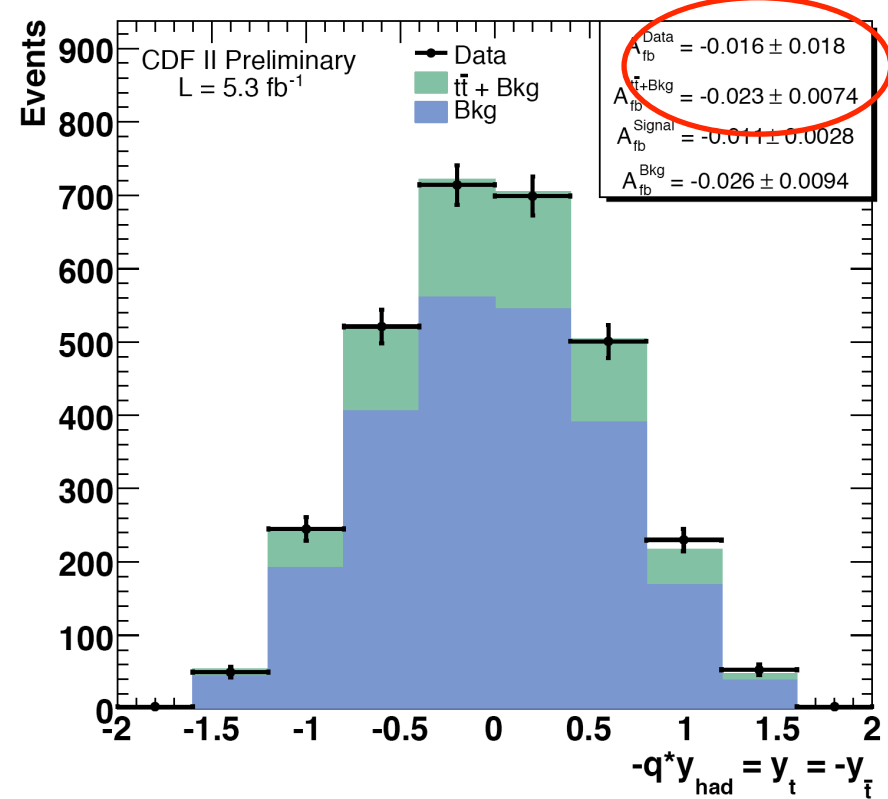tt rest frame   lab frame

backgrounds

- can be checked in events without b-tags. S:B = 0.3
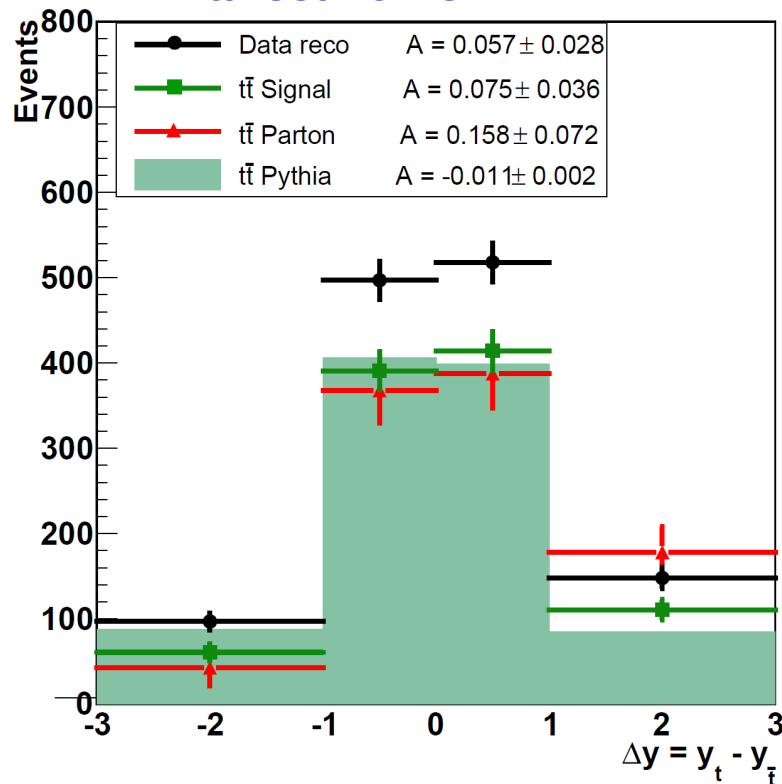- data and predictions in good agreement

tt rest frame

lab frame

4-bin measurements

sample	level	$A^{t\bar{t}}$	$A^{p\bar{p}}$
data	data	0.057 ± 0.028	0.073 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004	0.001 ± 0.003
data	signal	0.075 ± 0.037	0.110 ± 0.039
MC@NLO	$t\bar{t}$	0.024 ± 0.005	0.018 ± 0.005
data	parton	0.158 ± 0.074	0.150 ± 0.055
MCFM	parton	0.058 ± 0.009	0.038 ± 0.006

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4-bin measurements

tt rest frame

Data reco	A = 0.057 ± 0.028
tt̄ Signal	A = 0.075 ± 0.036
tt̄ Parton	A = 0.158 ± 0.072
tt̄ Pythia	A = -0.011 ± 0.002

lab frame

Data reco	A = 0.073 ± 0.028
tt̄ Signal	A = 0.110 ± 0.036
tt̄ Parton	A = 0.150 ± 0.050
tt̄ Pythia	A = -0.007 ± 0.002
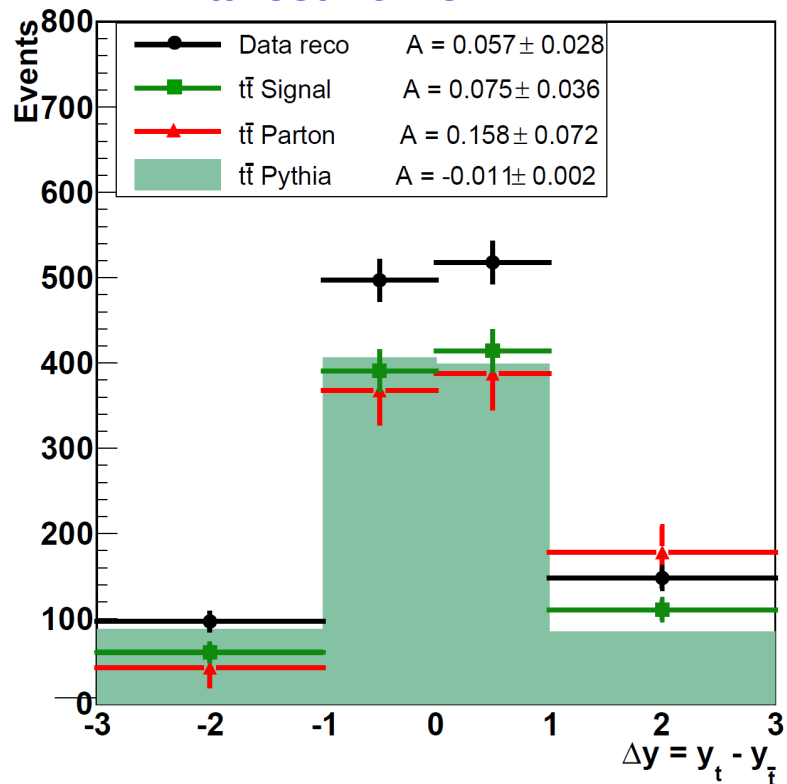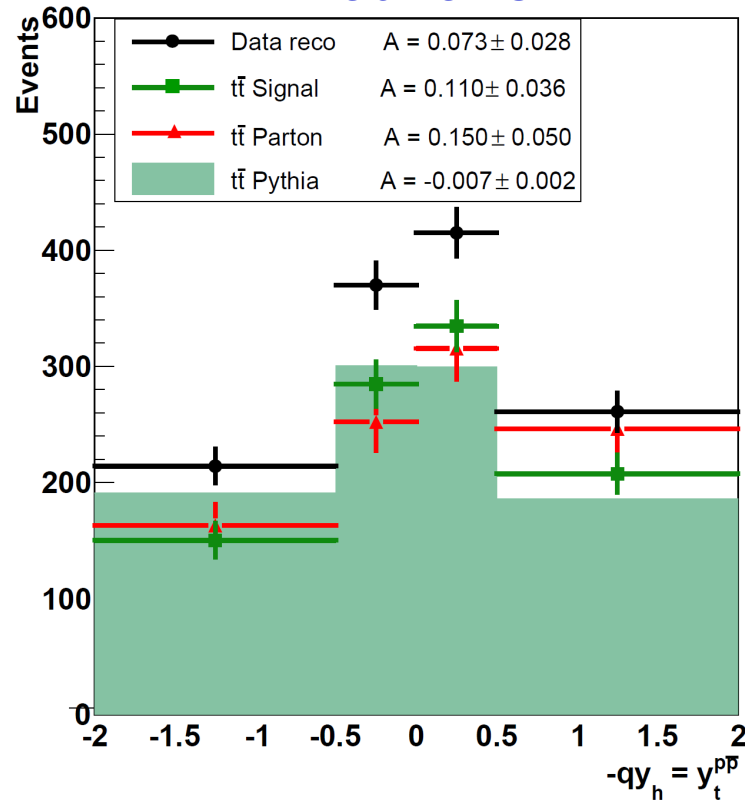
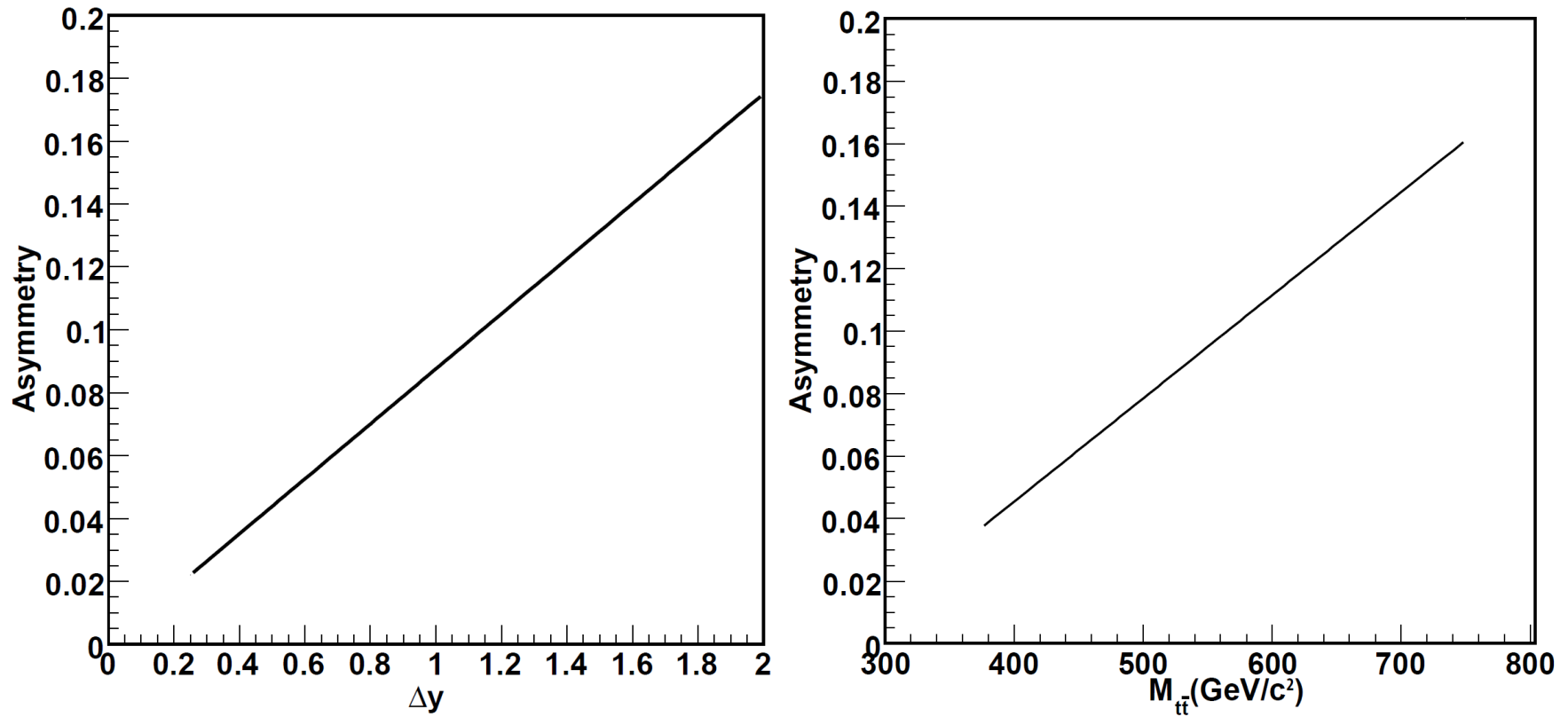| sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004
data	signal	0.075 ± 0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005
data	parton	0.158 ± 0.074
MCFM	parton	0.058 ± 0.009

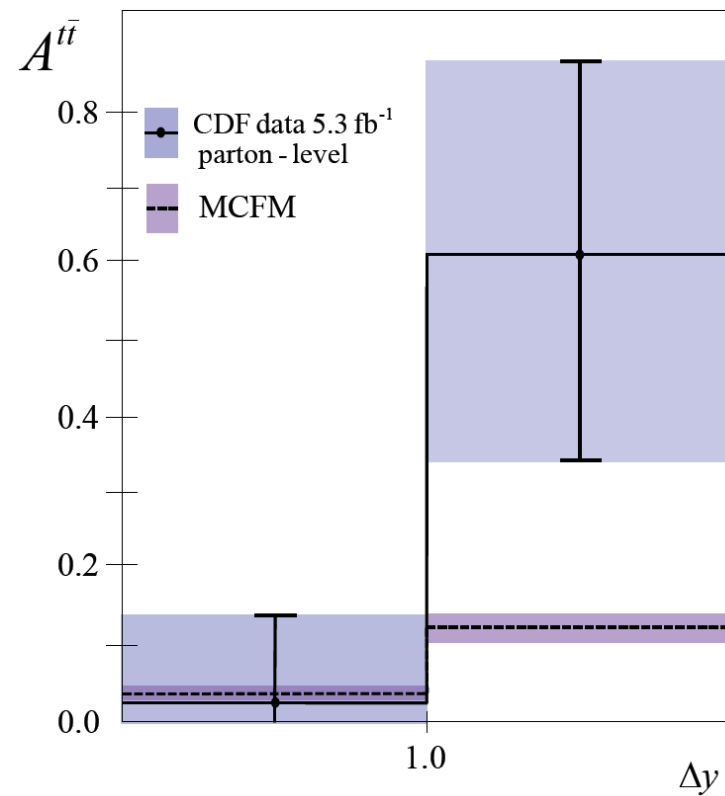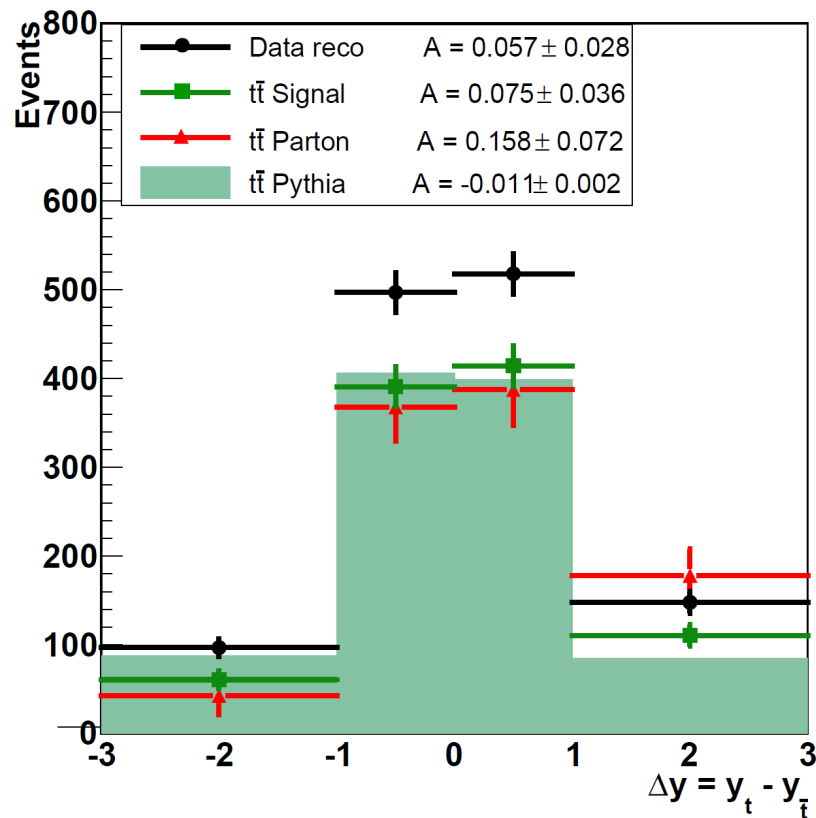n.b.
D0 signal level 4.3 fb^{-1}
0.08 ± 0.04
we agree!

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Asymmetry is a function of Δy and M_{tt}

- in tt frame, QCD asymmetry has linear dependence on $\Delta y,\ M_{t\bar{t}}$
- NLO prediction from MCFM

- $\Delta y,\ M_{t\bar{t}}$ dependence generally of interest in other theories

A(Δy), parton level, data

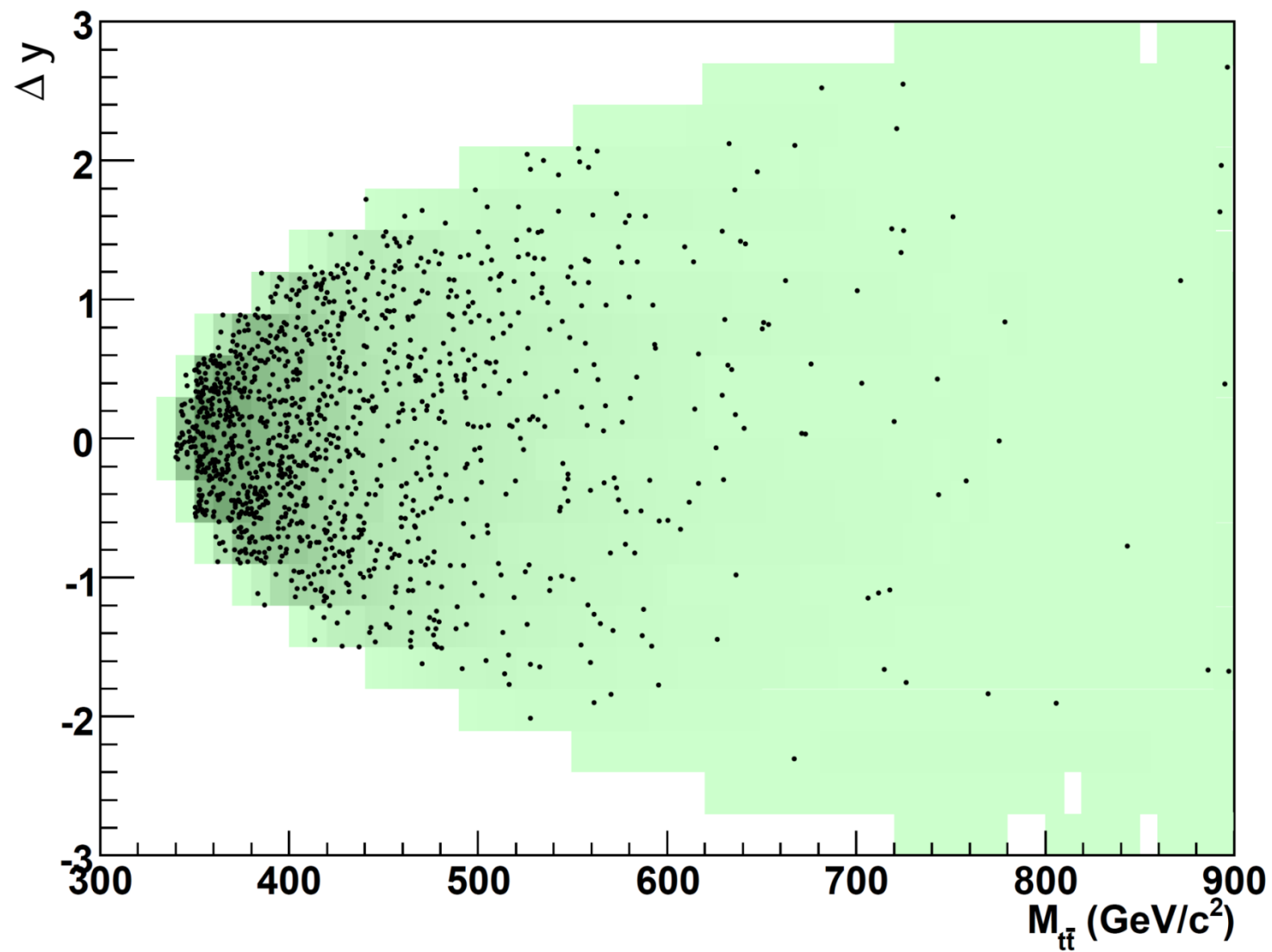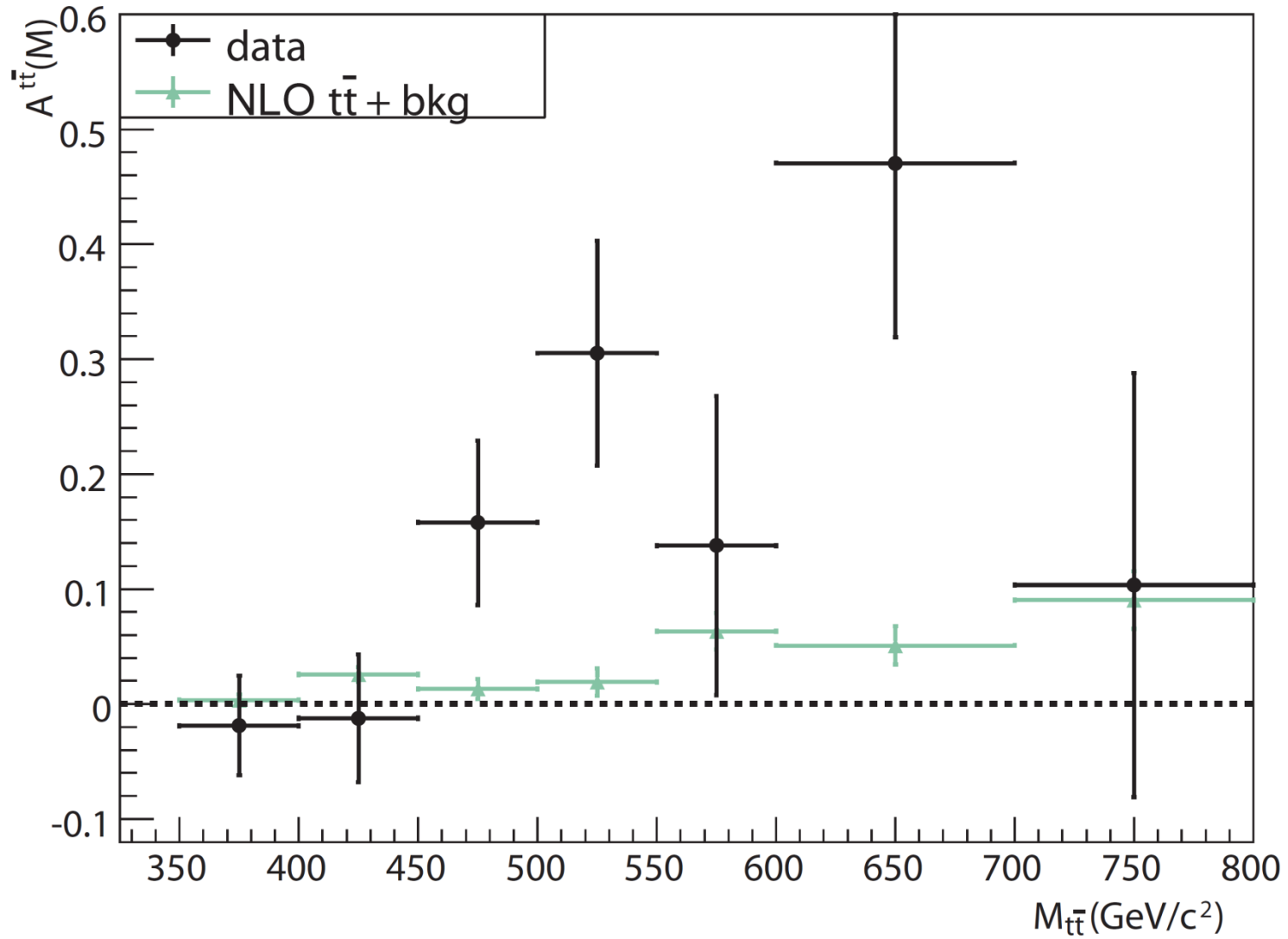| sample	level	$|\Delta y| < 1.0$	$|\Delta y| \geq 1.0$
data	data	0.021 ± 0.031	0.208 ± 0.062
data	parton	$0.026 \pm 0.104 \pm 0.056$	$0.611 \pm 0.210 \pm 0.147$
MCFM	parton	0.039 ± 0.006	0.123 ± 0.018

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Δy vs M_{tt}

FIG. 10: Top: The Δy—M plane. Each dot represents one event, while the shading is the approximate event probability in the standard PYTHIA based prediction.

A^{tt}(M$_{tt, i}$)

50 GeV bins   100 GeV bins

- How to quantify?   Two bins: high and low

color octet model

- need to test methodology on large asymmetry
- model: color octets with axial couplings
- this is a test sample. **not a hypothesis**

J. Naganoma

- after Ferrario and Rodrigo   arXiv:0906.5541
  - thanks to T. Tait for Madgraph
- If $g_A^q = -g_A^t$ get positive asymmetry
- Octet A
  - $g_v = 0$, $|g_A = 3/2|$
  - $M_G = 2.0$ TeV
  - $\sigma/\sigma_{sm} = 1.02$
  - ~ M_{tt} spectrum compares to Pythia
  - Model: True $A_{tt} = 0.16$ Reco $A_{tt} = 0.08$
  - Data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$
- Octet B
  - MG = 1.8 TeV. asymmetries bigger; σ, M_{tt} disrepancies bigger
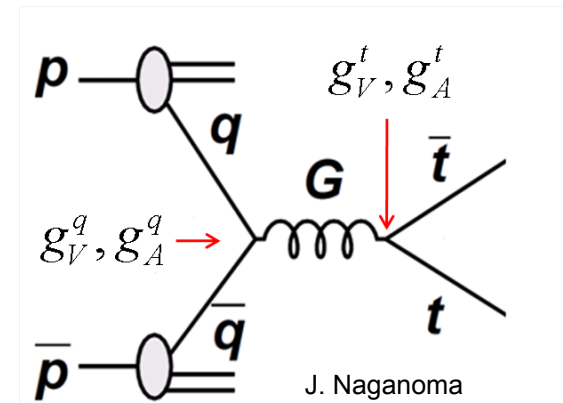
color octet model

- **Octet A detail** Δy $M_{t\bar{t}}$
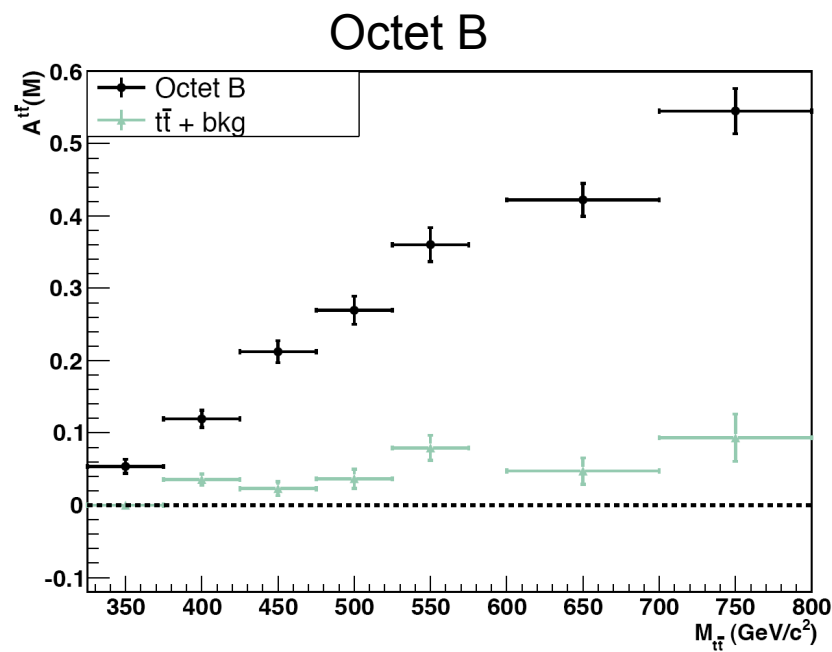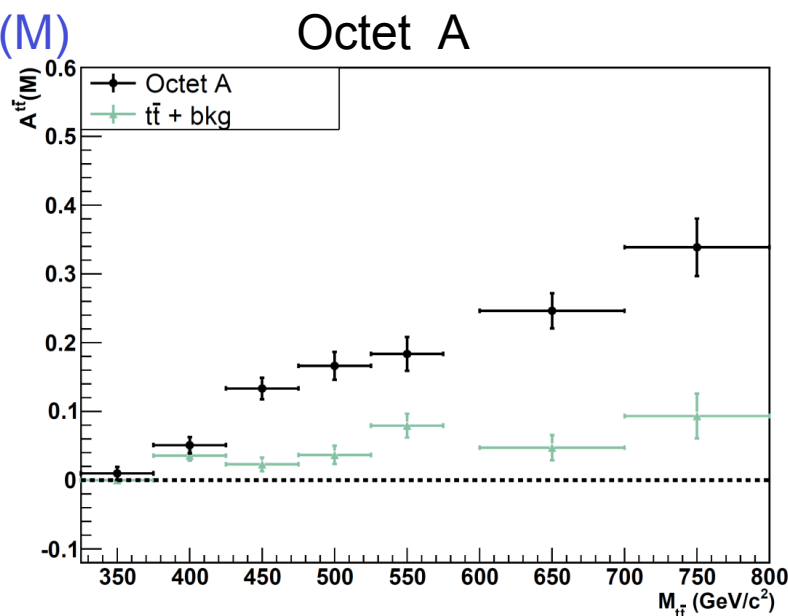
- **A(M)**   Octet A   Octet B

- binned like data, compared to MC@NLO
- reasonable model for the data

the two-bin boundary

- simplest A(M): two bins
- high and low mass
- where to put boundary?
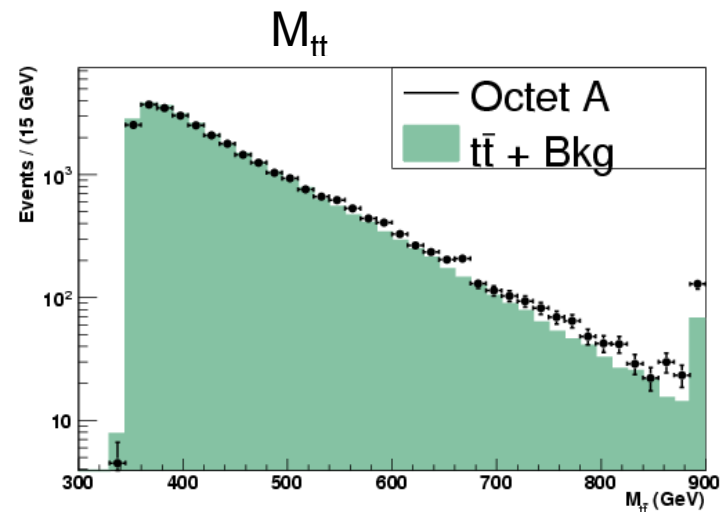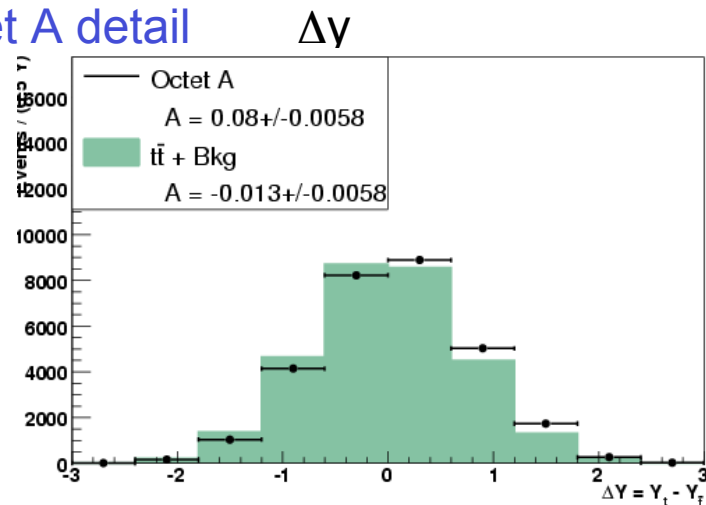- look at significance at high mass vs boundary
- ➢ best boundary: 450 GeV/c^2

bin-edge (GeV/c^2)	Octet A		Octet B	
	A^{tt}	significance	A^{tt}	significance
345	0.082 ± 0.028	2.90	0.168 ± 0.028	5.99
400	0.128 ± 0.036	3.55	0.235 ± 0.035	6.74
450	0.183 ± 0.047	3.91	0.310 ± 0.044	7.08
500	0.215 ± 0.060	3.60	0.369 ± 0.054	6.81
550	0.246 ± 0.076	3.25	0.425 ± 0.066	6.43
600	0.290 ± 0.097	2.97	0.460 ± 0.081	5.70

data: Δy at low and high mass
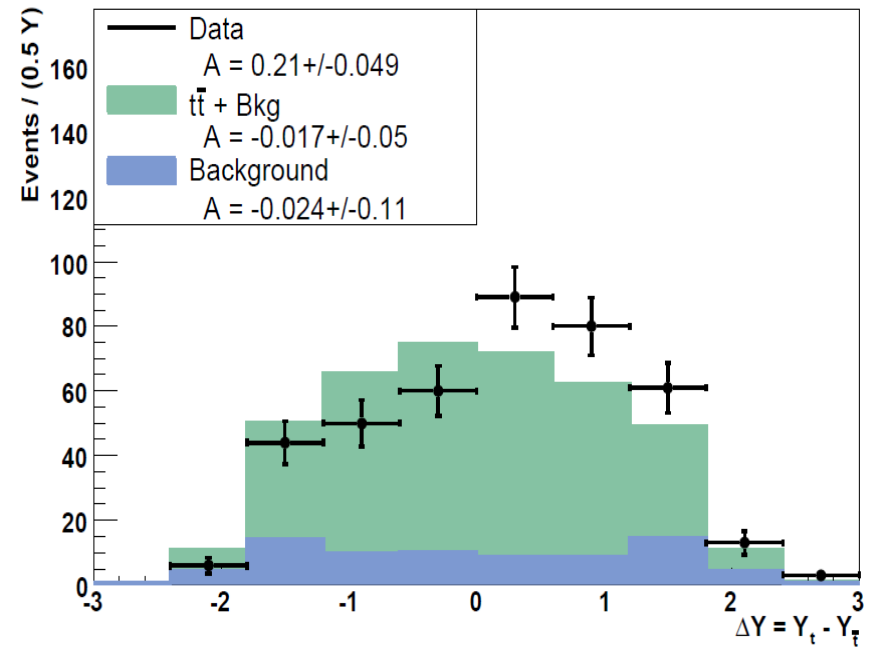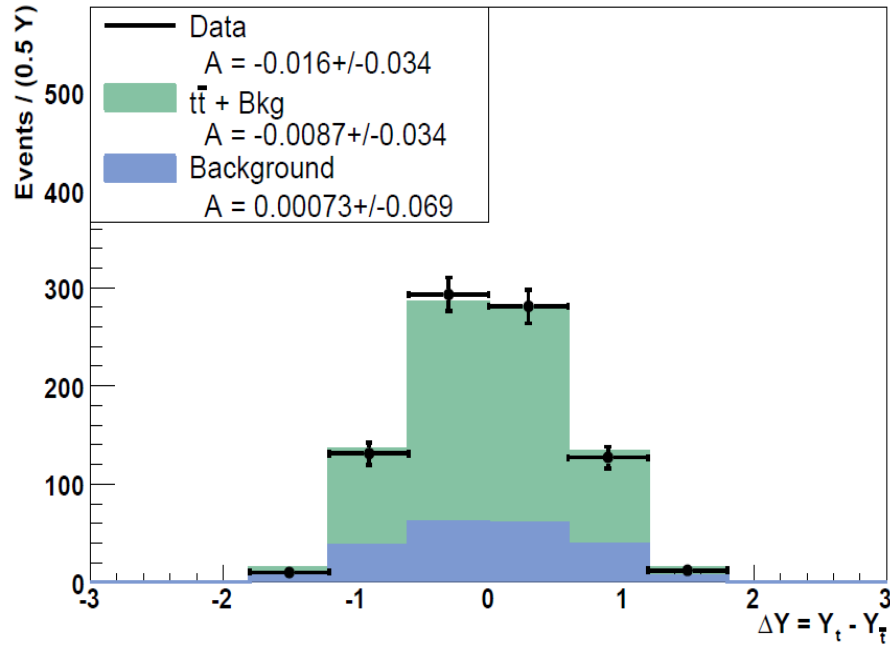
selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
reco data	0.057 ± 0.028	-0.016 ± 0.034	0.212 ± 0.049
MC@NLO	0.017 ± 0.004	0.012 ± 0.006	0.030 ± 0.007

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Δy at high mass by lepton charge

selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
A_{lh}^{+}	0.067 ± 0.040	-0.013 ± 0.050	0.210 ± 0.066
A_{lh}^{-}	-0.048 ± 0.039	0.020 ± 0.047	-0.210 ± 0.071

Δy at high mass by lepton charge
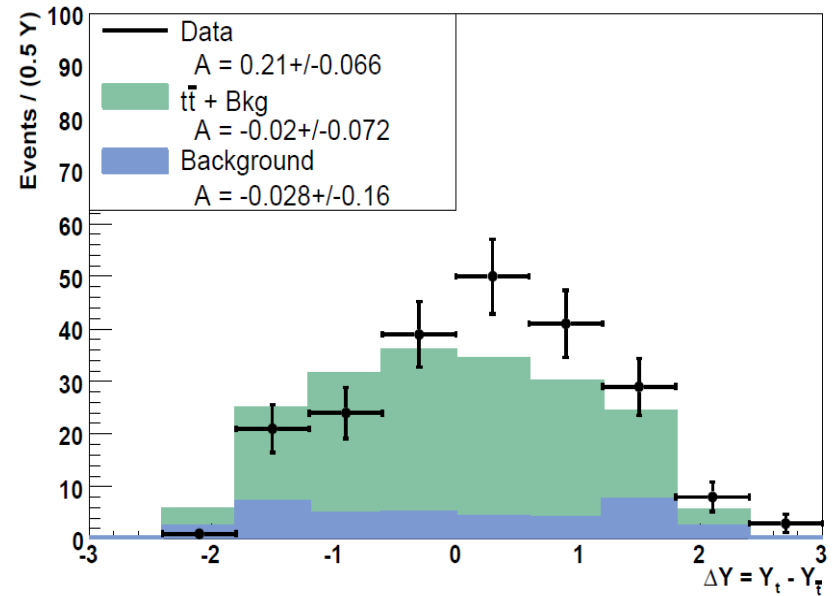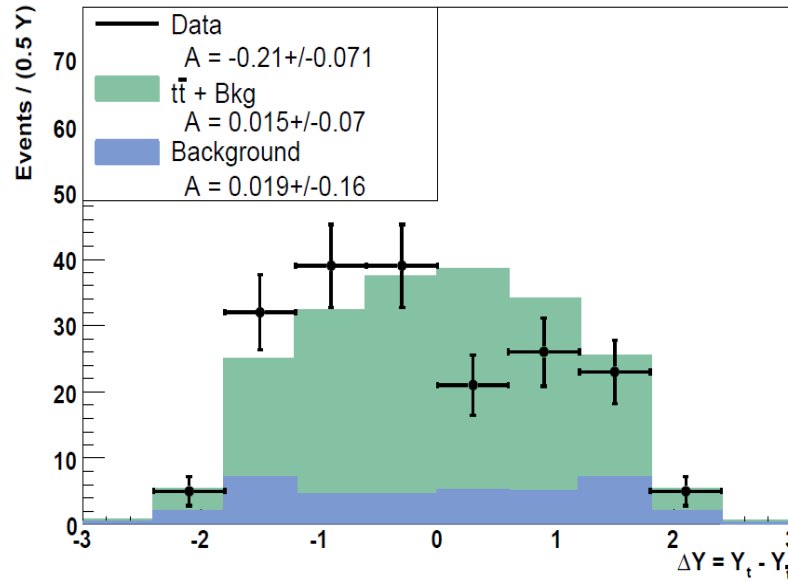
selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
A_{lh}^{+}	0.067 ± 0.040	-0.013 ± 0.050	0.210 ± 0.066
A_{lh}^{-}	-0.048 ± 0.039	0.020 ± 0.047	-0.210 ± 0.071

- consistent with CP conservation
- argues against experimental artifact, as detection/reconstruction are sign independent

unfold to the parton level

- dN/dy parton level histogram
  - parton level bins j w/ contents Pj

- the top data signal
  - $T_i = S_{ij} \times A_j \times P_j$

- where
  - the A_j are the acceptances for each bin
  - the S_{ij} are the bin-to-bin migration ratios
  - both measured with symmetric Pythia

- dN/dy data level histogram
  - parton level bins j w/ contents Pj
  - data: in bins i w/ contents $D_i = T_i + B_i$

- to propagate data to parton level:
  - $P_j = A_j^{-1} \times S_{ji}^{-1} \times (D_i - B_i)$

- result is optimized when number of bins = 4

BUT NOW:

4 bins in Δy and M_{tt}

low mass forward
low mass backward
high mass forward
high mass backward

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tests of unfold procedure

Sample	$A^{t\bar{t}}$ level	$M_{t\bar{t}} < 450$ GeV/c^2	$M_{t\bar{t}} \geq 450$ GeV/c^2
PYTHIA	MC truth	0.002	0.001
	reconstructed	-0.011 ± 0.006	-0.013 ± 0.008
	corrected	0.001 ± 0.018	0.006 ± 0.014
MC@NLO	MC truth	0.043	0.070
	reconstructed	0.015 ± 0.006	0.043 ± 0.009
	corrected	0.066 ± 0.014	0.086 ± 0.011
Octet A	MC truth	0.081	0.276
	reconstructed	0.024 ± 0.035	0.183 ± 0.010
	corrected	0.054 ± 0.022	0.308 ± 0.016
Octet B	MC truth	0.150	0.466
	reconstructed	0.078 ± 0.036	0.310 ± 0.009
	corrected	0.187 ± 0.024	0.476 ± 0.015

sys uncertainty of unfold procedure

Source	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
background size	0.017	0.032
background shape	0.003	0.003
JES	0.005	0.012
ISR/FSR	0.012	0.008
color reconnection	0.009	0.004
PDF	0.018	0.004
physics model	0.035	0.035
total	0.047	0.049

TABLE XII: Systematic uncertainties in the two-mass bin unfold

A^{tt} at high and low mass: data, signal, parton level

selection	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
data	-0.016 ± 0.034	0.210 ± 0.049
MC@NLO $t\bar{t}$+bkg	$+0.012 \pm 0.006$	0.030 ± 0.007
data signal	$-0.022 \pm 0.039 \pm 0.017$	$0.266 \pm 0.053 \pm 0.032$
MC@NLO $t\bar{t}$	$+0.015 \pm 0.006$	0.043 ± 0.009
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

TABLE XIII: Asymmetry $A^{t\bar{t}}$ at high and low mass compared to prediction.

A^{tt} at high and low mass: parton level
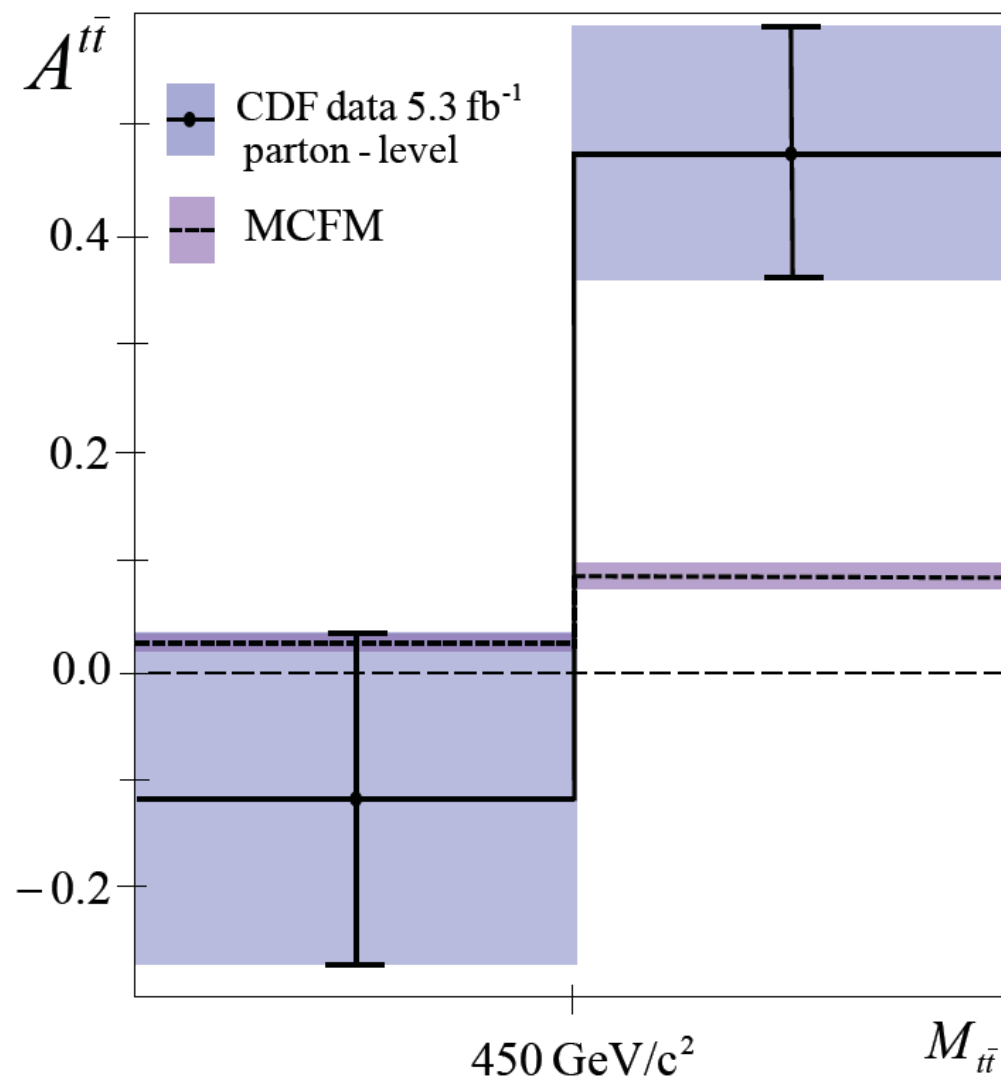
Studies of A^{tt} at the data level

selection	N events	all M	$M < 450\ \mathrm{GeV}/c^2$	$M \geq 450\ \mathrm{GeV}/c^2$
standard	1260	0.057±0.028	-0.016±0.034	0.212±0.049
electrons	735	0.026±0.037	-0.020±0.045	0.120±0.063
muons	525	0.105±0.043	-0.012±0.054	0.348±0.080
data $\chi^2 < 3.0$	338	0.030±0.054	-0.033 ± 0.065	0.180 ± 0.099
data no-b-fit	1260	0.062±0.028	0.006 ± 0.034	0.190 ± 0.050
data single b-tag	979	0.058±0.031	-0.015±0.038	0.224±0.056
data double b-tag	281	0.053±0.059	-0.023±0.076	0.178±0.095
data anti-tag	3019	0.033±0.018	0.029±0.021	0.044±0.035
pred anti-tag	-	0.010±0.007	0.013±0.008	0.001±0.014
pre-tag	4279	0.040±0.015	0.017±0.018	0.100±0.029
pre-tag no-b-fit	4279	0.042±0.015	0.023±0.018	0.092±0.029

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Jet multiplicity dependence

- the NLO QCD asymmetry has a strong N_{jet} dependence

selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
inclusive	0.024 ± 0.004	0.015 ± 0.005	0.043 ± 0.007
4-jet	0.048 ± 0.005	0.033 ± 0.006	0.078 ± 0.009
5-jet	-0.035 ± 0.007	-0.032 ± 0.009	-0.040 ± 0.012

- data: the high mass asymmetry is significantly reduced for 5 jet events

selection	N events	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
data 4-jet	939	0.065±0.033	-0.023±0.039	0.26±0.057
data 5-jet	321	0.034±0.056	0.0049±0.07	0.086±0.093

- need to study other models, color flow, asymmetry reco in ttj

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Frame dependence

- a selection of cross-checks in the lab frame using $-qy_h = y_t^{p\bar{p}}$

selection	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
data reco	0.073±0.028	0.059±0.034	0.103±0.049
MC@NLO	0.017±0.004	-0.008±0.005	0.022±0.007
A_h^+	-0.076±0.039	-0.085±0.047	-0.053±0.072
A_h^-	0.070±0.040	0.028±0.050	0.148±0.066
single b-tags	0.095±0.032	0.079±0.034	0.130±0.057
double b-tags	-0.004±0.060	-0.023±0.076	0.028±0.097

- the high mass asymmetry is less significant in the lab frame
  - like QCD ?
- the high mass double tag asymmetry is low in the lab frame
  - statistics?
  - $|\eta| < 1.0$ for b-tags. acceptance + physics?

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Summary

- Inclusive A in lab and tt frames in 2 sigma excess over SM
- Consistent with CP conservation

- A^{tt} has a strong dependence on Δy, M_{tt}
- For $M_{tt} > 450$ GeV/c^2

$$A^{tt}_{reco} = 0.210\pm0.049, \quad A^{tt}_{parton} = 0.475\pm0.112$$
$$A^{tt}_{NLO\ reco} = 0.043\pm0.006 \quad A^{tt}_{MCFM} = 0.088\pm0.013$$

- The asymmetry at high mass is consistent with CP conservation
- Most cross-checks rule out non-physics, although a few puzzles

➢ The modest inclusive asymmetry originates with a significant effect at large Δy, M_{tt}

- There is a lot more work to do!